



# E951 15T Pulsed Magnet for Mercury Target Development

## Neutrino Factory and Muon Collider Collaboration

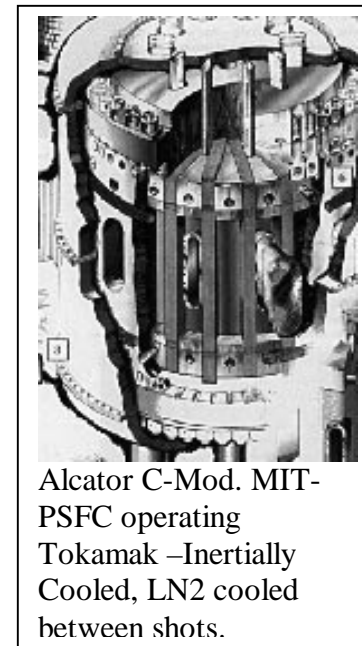
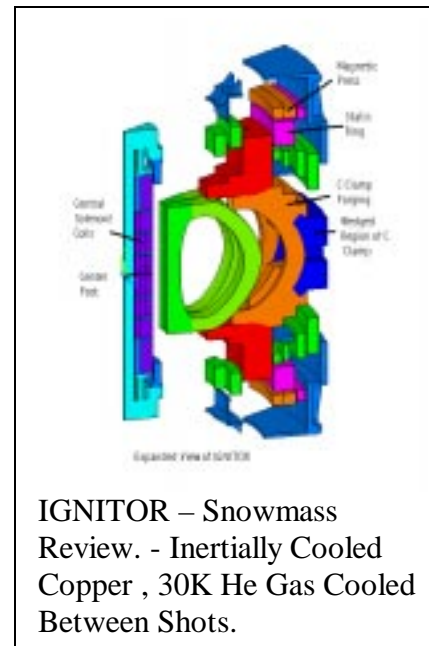
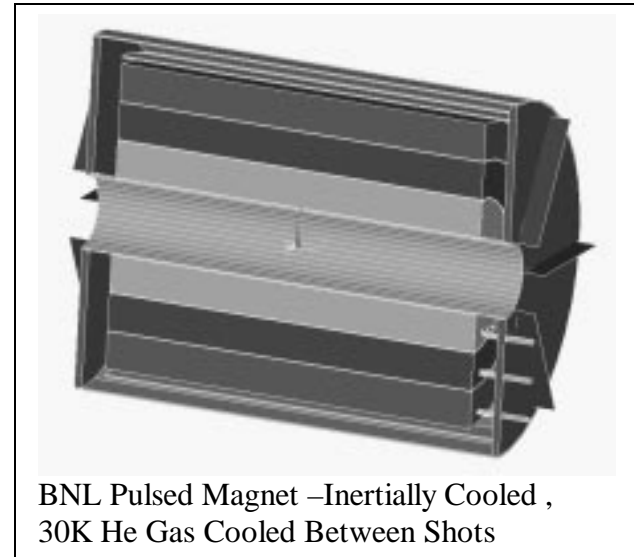
2002

Peter H. Titus

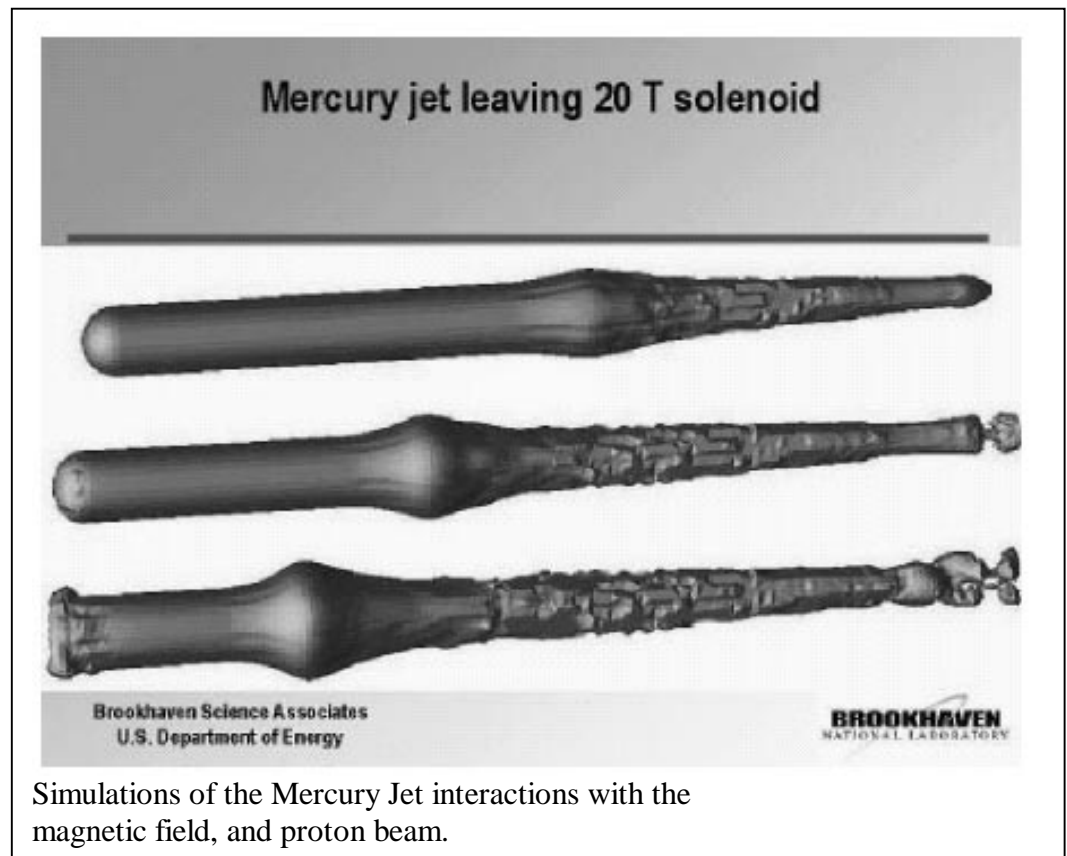
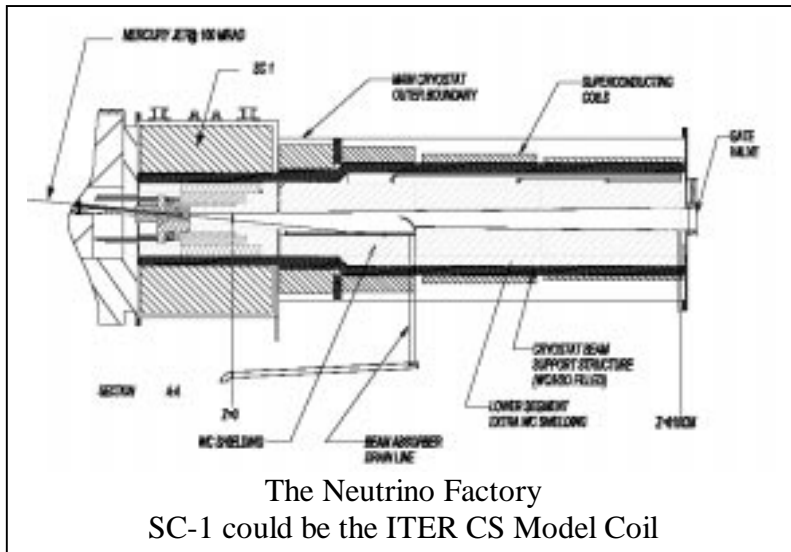
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*BNL pulsed magnet design builds off of copper magnet experience in fusion research:*



## *The Purpose of the Experiment is to Study Mercury Targets for Neutrino Beams and a Muon Collider Source*



Cost issues dictate a modest coil design.

Power supply limitations dictate a compact, low inductance, high packing fraction design.

A three segment, layer wound solenoid is proposed for the pulsed magnet.

Phased manufacture is supported. The third segment may be purchased and installed in the cryostat later

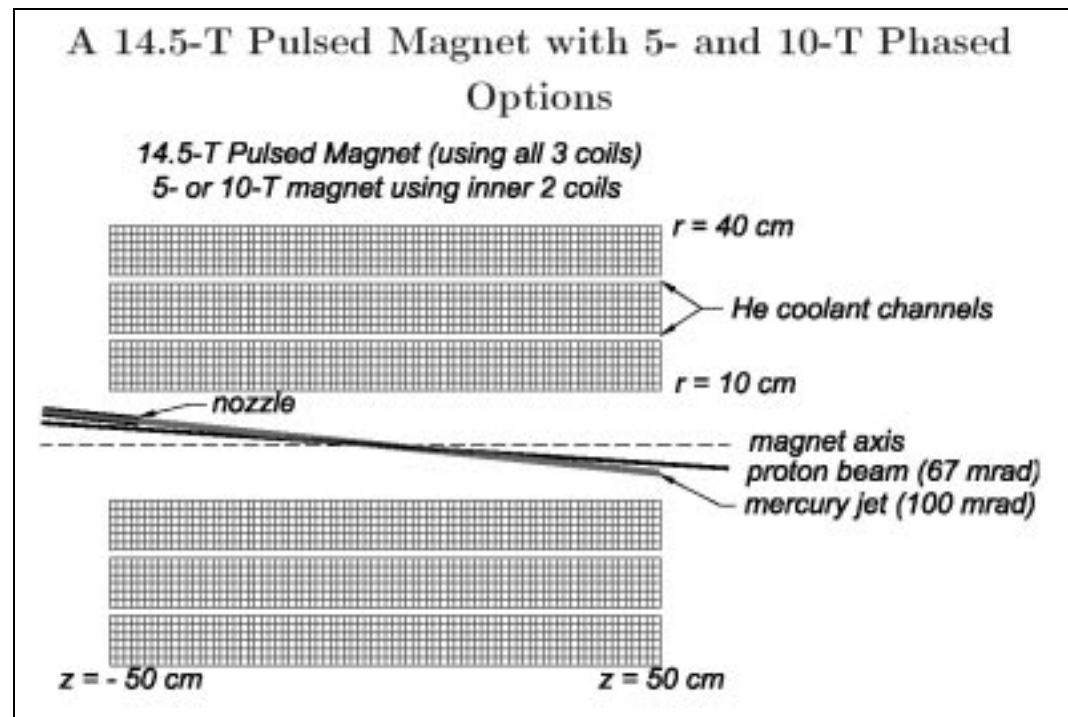
The conductor is half inch square, cold worked OFHC copper.

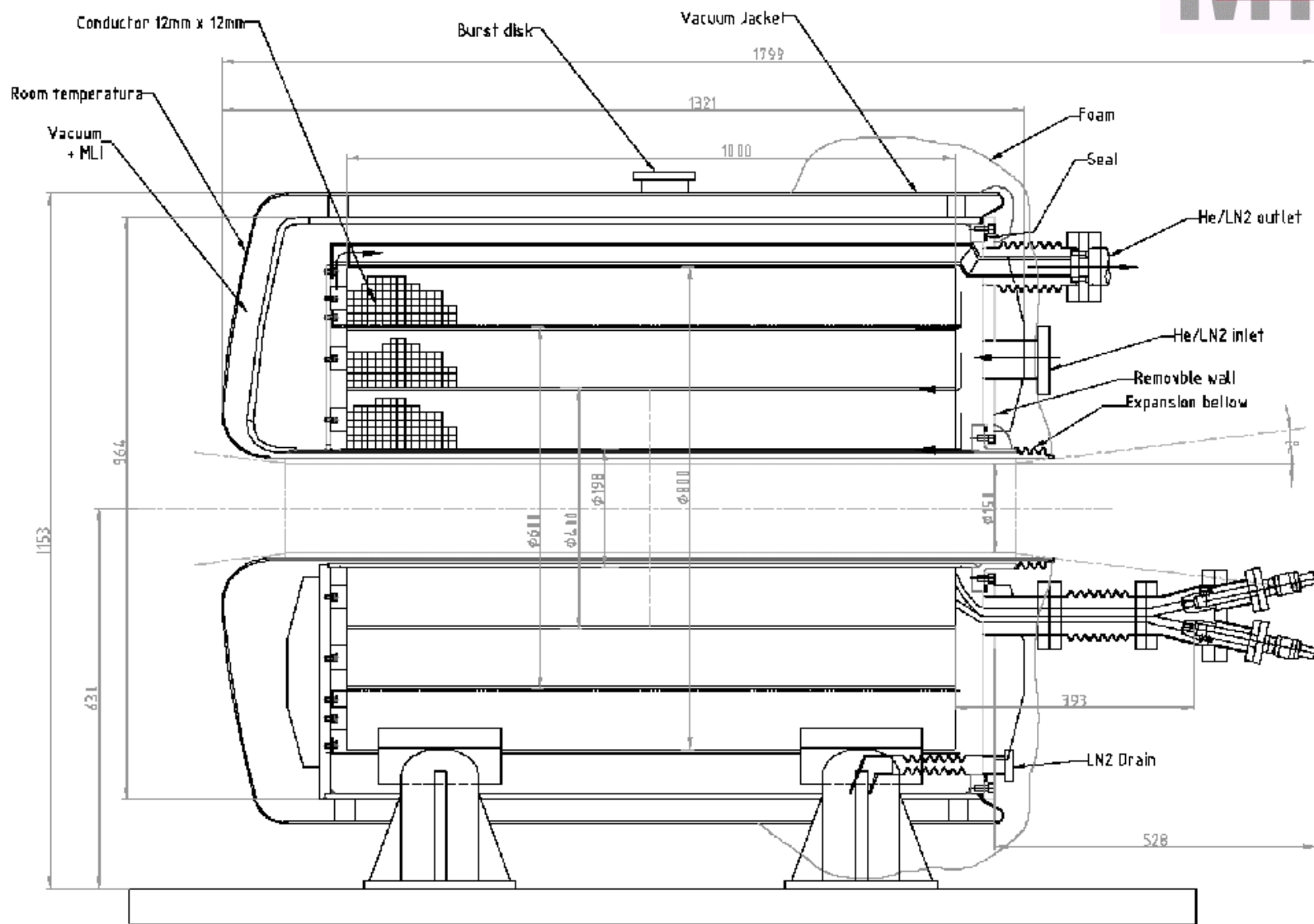
The coil is inertially cooled with options for liquid nitrogen or gaseous Helium cooling between shots. Coolant flows through axial channels in the coil.

For the same packing fraction, a hollow conductor would have a 1.4mm diameter hole

The coil will be epoxy impregnated. Wound coils of this small radius, using cold worked conductor, retain internal elastic stresses from the winding process, and if not impregnated, require elaborate clamping mechanisms to have the coil retain it's shape.

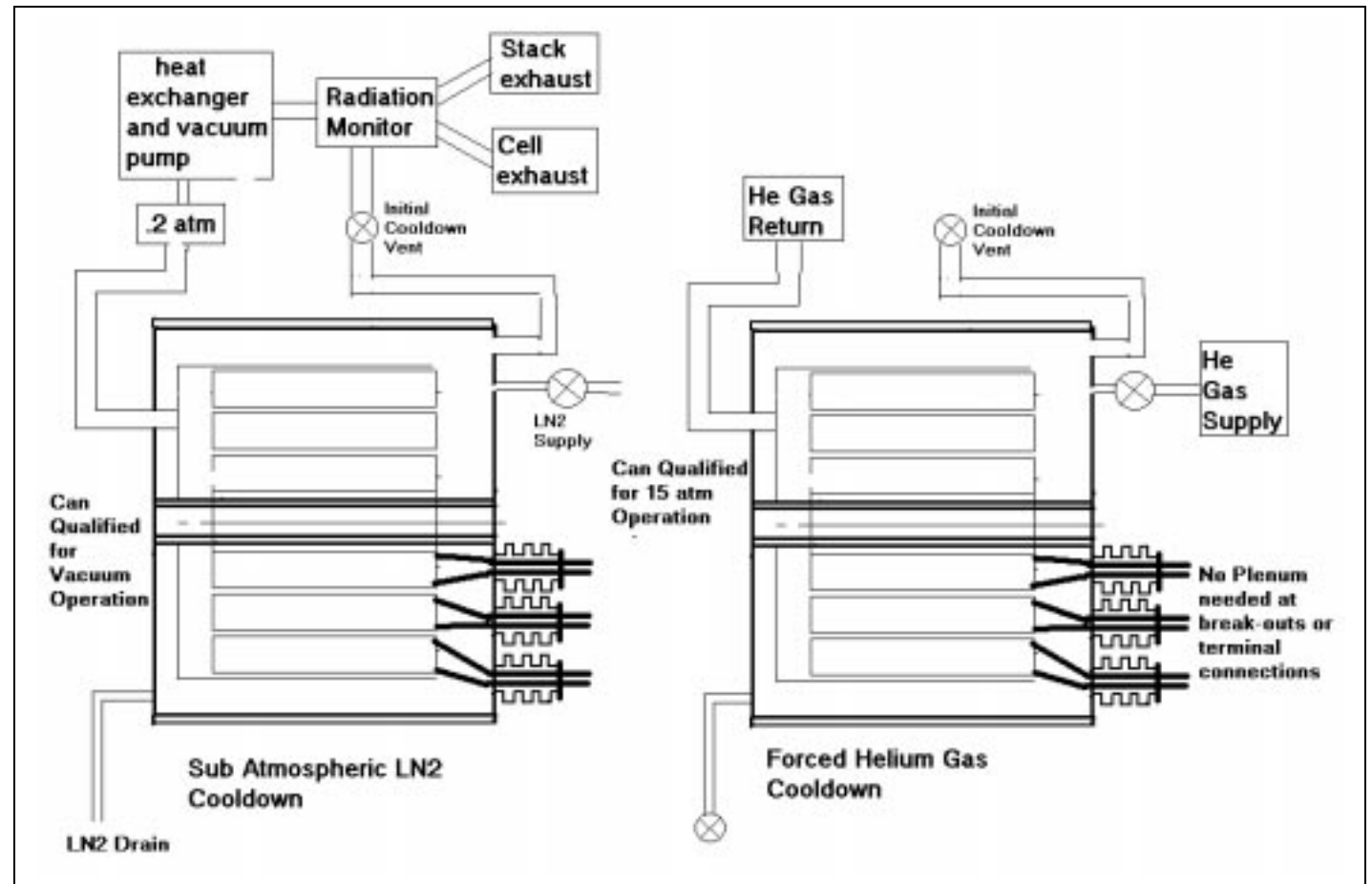
Bob Weggel has performed the coil/power supply simulations. He has picked operating temperatures, and basic coil build.





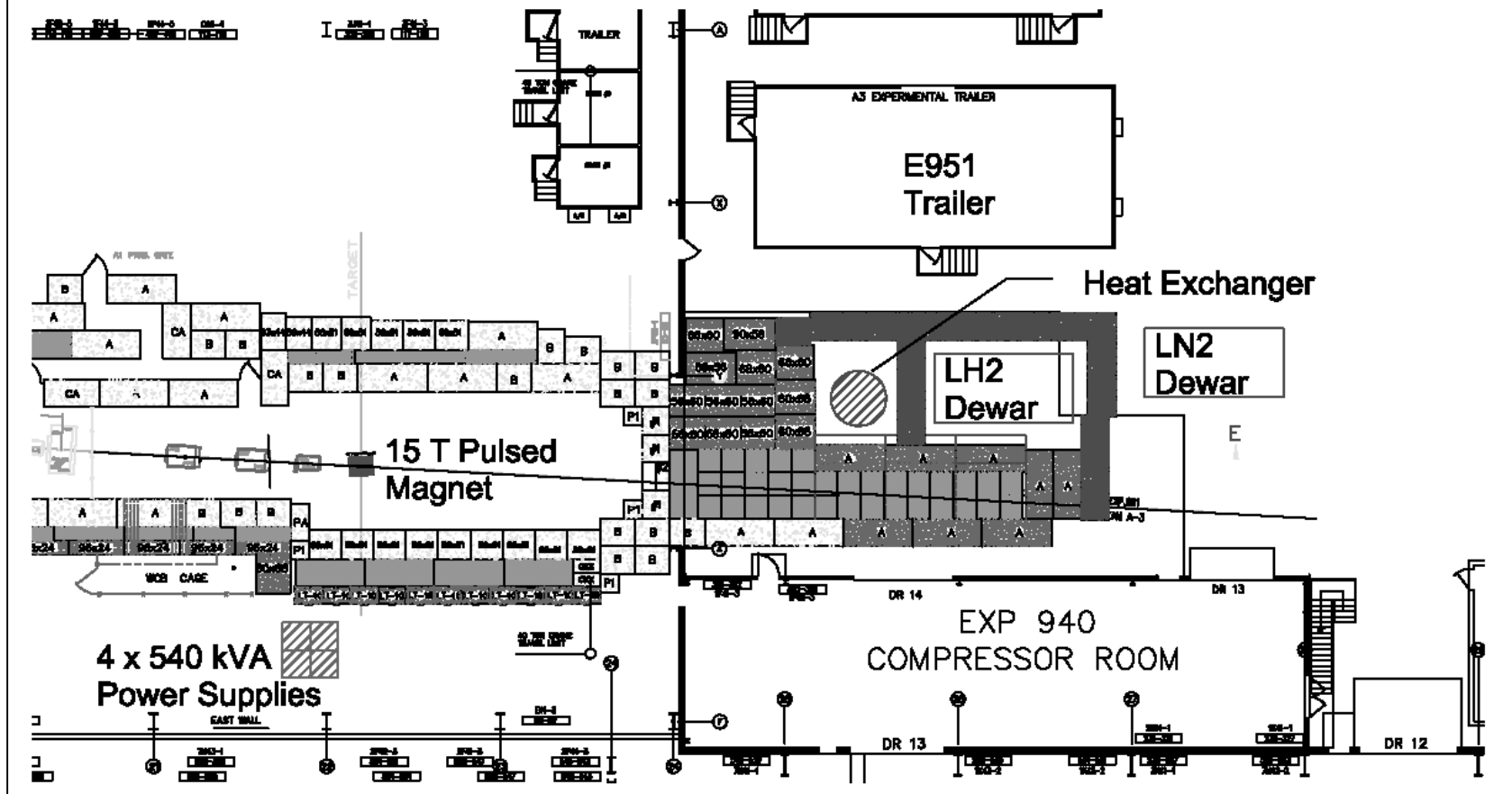
## Proposed Operational Scenarios

The coil and cryostat are designed for two cooling modes and three fields



Case #	Peak Field	Coolant	T after pulse	T coolant	Start Bulk Temp
1	5T	Helium Gas	90K	66K	84K
1a	5T	LN2	90K	66K	84K
2	10T	Helium Gas	96K	66K	74K
2a	10T	LN2	96K	66K	74K
3	15T	Helium Gas	78K	22K	30K

# Pulsed Magnet System Layout at the AGS



## Coil Builds used in the finite Element Models:

#	r	z	dr	dz	nx	ny
1	.15	0	.098	1.0	16	16
3	.25	0	.098	1.0	16	16
5	.35	0	.098	1.0	16	16

## Coil Description:

	Mode 1	Mode 2	Mode3
Number of Segments operating:	2	2	3
Number of turns per segment	624	624	624
Total number of turns active	1248	1248	1872
Layers in each coil segment	8	8	8
Turns per layer	78	78	78
Conductor radial thickness	.0116698 m .45944 in	.0116698 m .45944 in	.0116698 m .45944 in
Conductor Axial thickness	.012516m .49274359 in	.012516m .49274359 in	.012516m .49274359 in
Max Operating Field Bore CL	5T	10T	15.0T
Max Field at Magnet			
Max Terminal Current	3600A	7200A	7200A
Coolant Working Fluid	77K LN2	65K LN2	30 K Helium Gas
Terminal Voltage	150V	300V	300V
Layer to Layer Volts	18	36	24
Turn-to-Turn Volts	0.12	0.24	.16
Design Life			1000 full power pulses
Cryostat Pressure -Initial Operating			15 atm
Cryostat Pressure – During Cooldown			20 atm max

## Structural Design Criteria

Lacking a specific design code jurisdiction, fusion project criteria are used for guidance in coil design [1]

The referenced FIRE design document allows the primary membrane stress to be based on the lesser of  $2/3$  of the Yield Strength ( $S_y$ ) or  $1/2$  of the Ultimate Strength ( $S_u$ ). The ASME Code bases the primary stress on  $1/3$  ultimate. The fusion project based criteria is based on a distinction between coils that are supported by cases and those that are not.

For structural elements ASME -like criteria are adopted with membrane stresses remaining below the maximum allowable stress,  $S_m$ , where  $S_m$  is the lesser of  $2/3 \cdot \text{yield}$  or  $1/3$  ultimate.

Bending discontinuity, and secondary stresses are treated in a manner similar to the ASME Code.

Guidance for bolting and column buckling is taken from AISC, with average net section bolt stresses kept below  $0.6 \cdot \text{yield}$ . Yield Strength and Tensile Strength properties are taken at the loaded temperature.

The cryostats are to be qualified in accordance with ASME VIII. Qualification of all the weld details, shell thicknesses, nozzle reinforcements, and saddle or support details of these vessels will be done at the final design stage. The conceptual design sizing presented here is intended to ensure adequate space allocation and cold mass performance.

The magnet is to be seismically qualified in accordance with the Uniform Building Code.



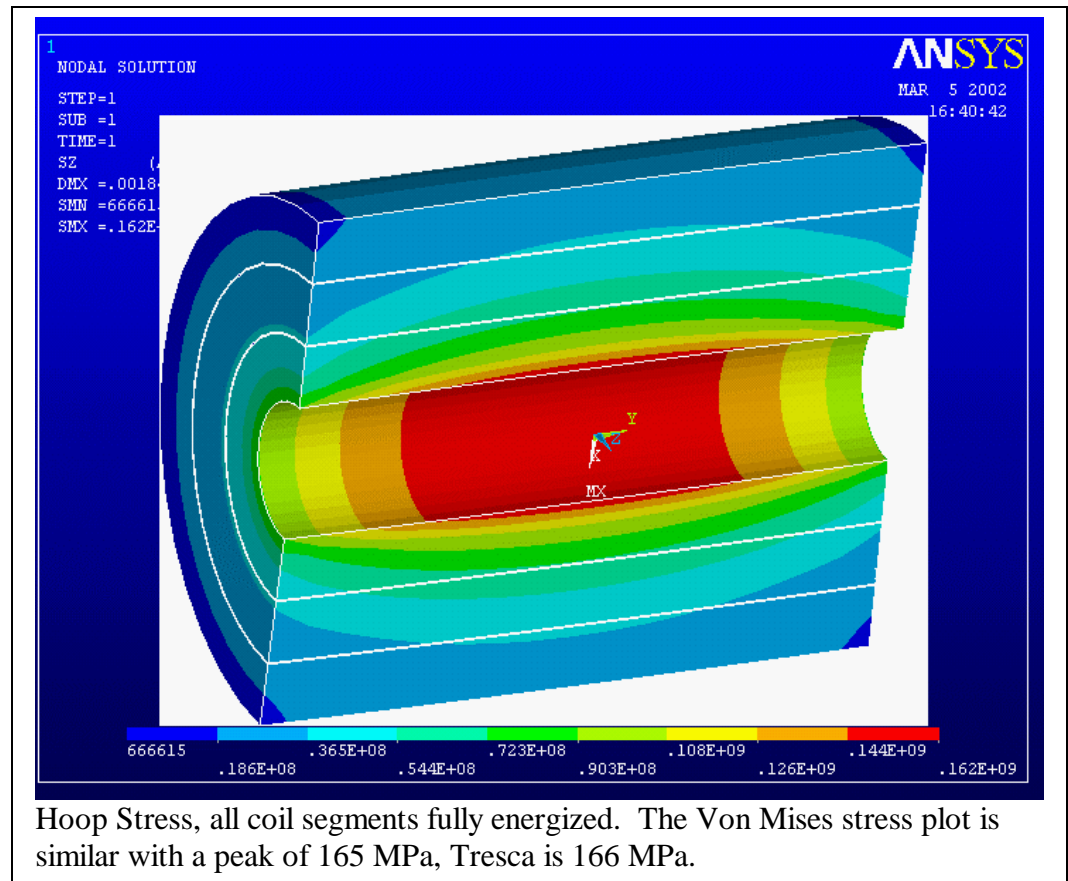
## Coil Stress Analysis

The three segment coil has three operational modes, two of which are structurally significant.

The full performance configuration is limiting in terms of hoop stress and equivalent stress. It also has some radial stresses that will have to be mitigated with parting planes at the segment boundaries, or within the winding.

In the initial operating mode the outer coil segment is not energized. This induces some differential Lorentz forces and differential temperatures, that cause shear stresses between segments.

For Fusion magnets the inner skin of the solenoid is allowed to reach the yield - Treating this stress as a bending stress with a  $1.5 \cdot S_m$  allowable with  $S_m$  based on  $2/3$  Yield.



Interpolated values:, Work hardened copper-, OFHC c10100 60% red

temp deg k	77	90	100	125	150	200	250	275	292
yield	374	369.	365.	356.	347.	328.	317.	312.	308.
ultimate	476.	466.	458.	439.	420.	383.	365.	356.	350.

## **Conductor Cold Work Spec**

If the highly cold-worked copper is chosen for the winding, the conductor allowable near the inside radius of the coil would be 365MPa. The max stress in the three segment coil is 166 MPa. With this stress level, it is expected that half hard copper could be used, simplifying the winding process.

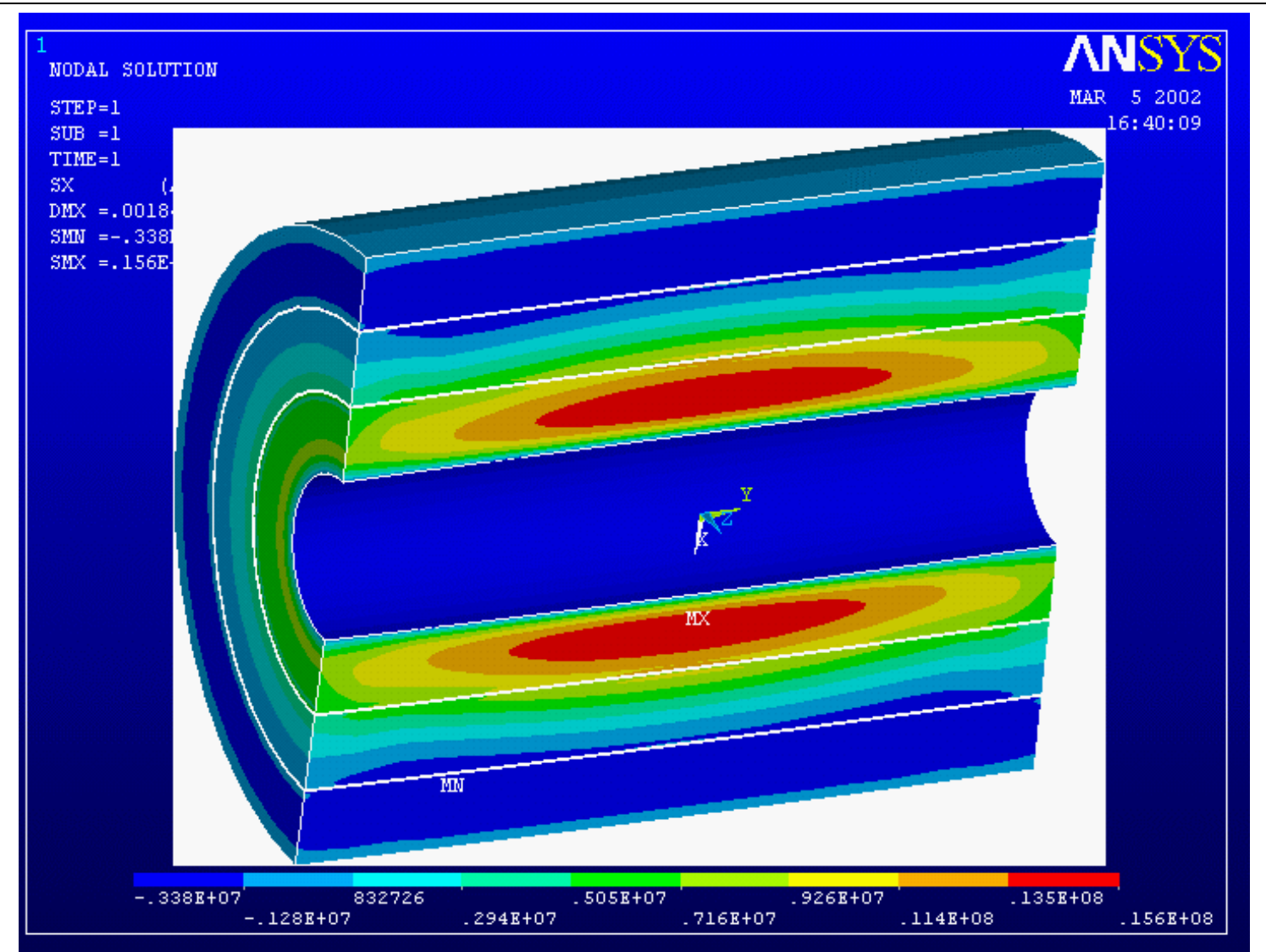
Half hard copper may still be too difficult for the Inner coil winding radius.

Planned Analysis:

Elastic-Plastic analysis of the tight radius bending operation to see if this introduces sufficient cold work to satisfy the stress allowables.



## Radial Tension Stress, All Coils Fully Energized.



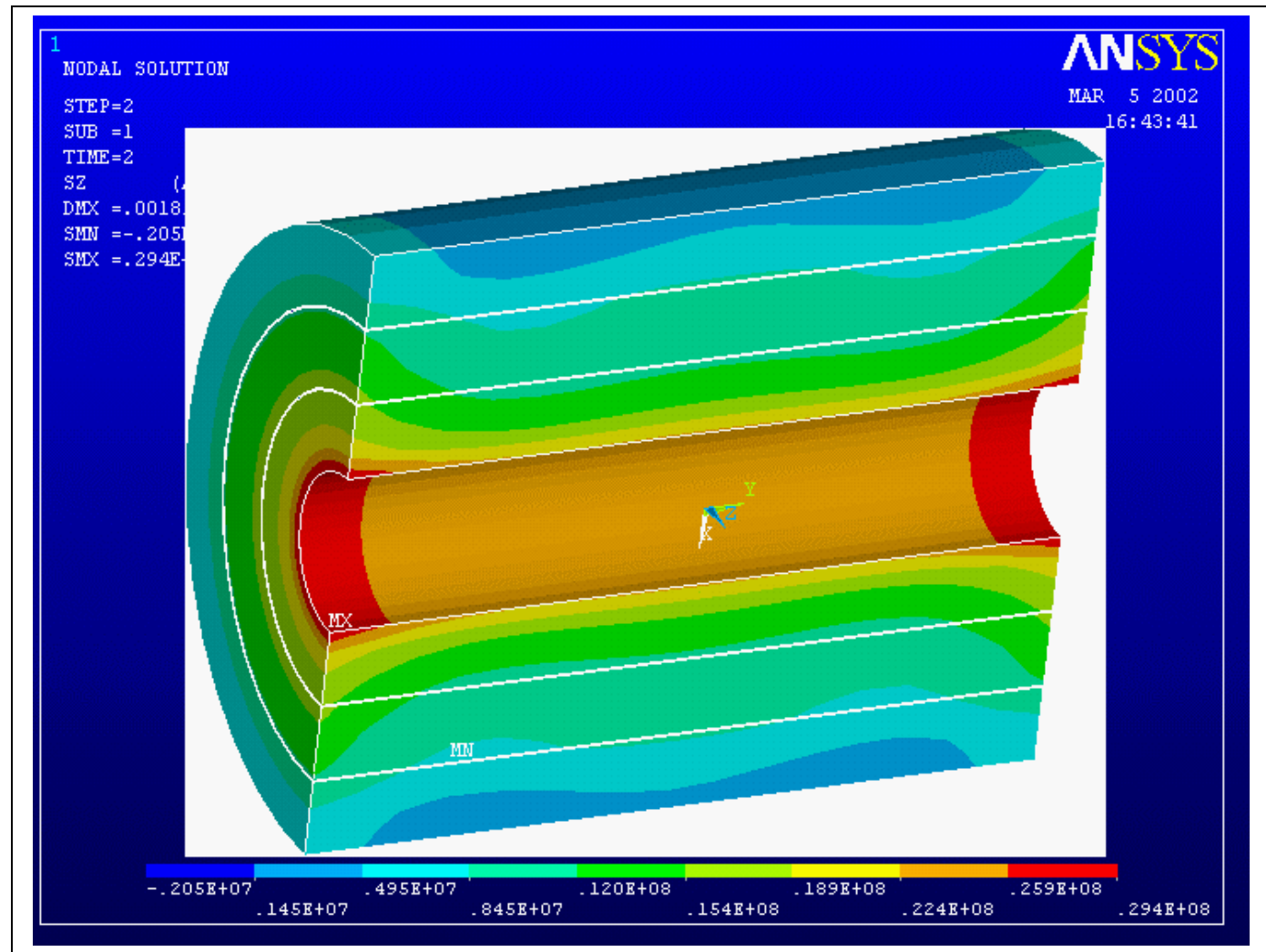
There is about an MPa of tension at the boundary between the first and second module. To avoid damage to the channel ligaments, a parting plane will be incorporated in the channel detail. This needs to occur in the ligament to retain thermal connection with the coolant in the channel.



**Operating Mode 2,  
10T**

**Hoop Stress  
With only the Inner  
Two Segments  
Energized.**

**Peak Hoop Stress is  
Only 29.4 MPa**

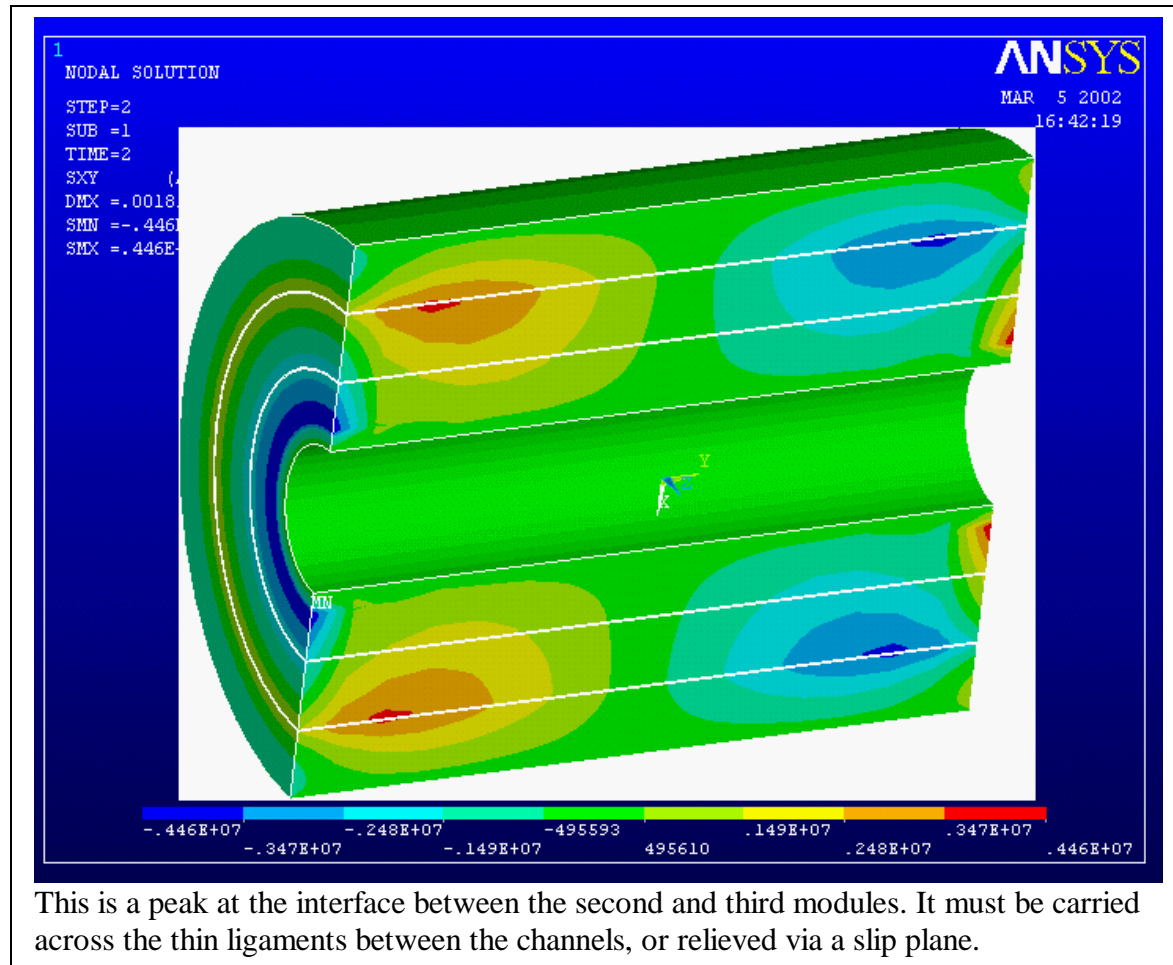
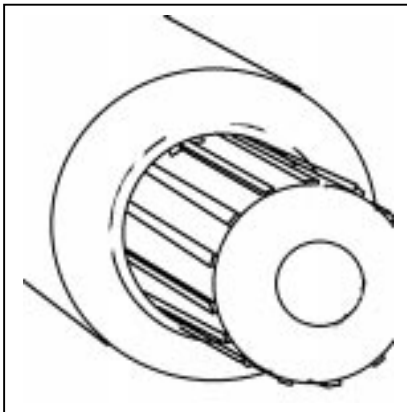




Operating Mode 2, 10T

Smeared radial-axial shear stress with the inner two segments energized.

*Channel Ligaments would be too weak to support this – Slip Planes are Used.*

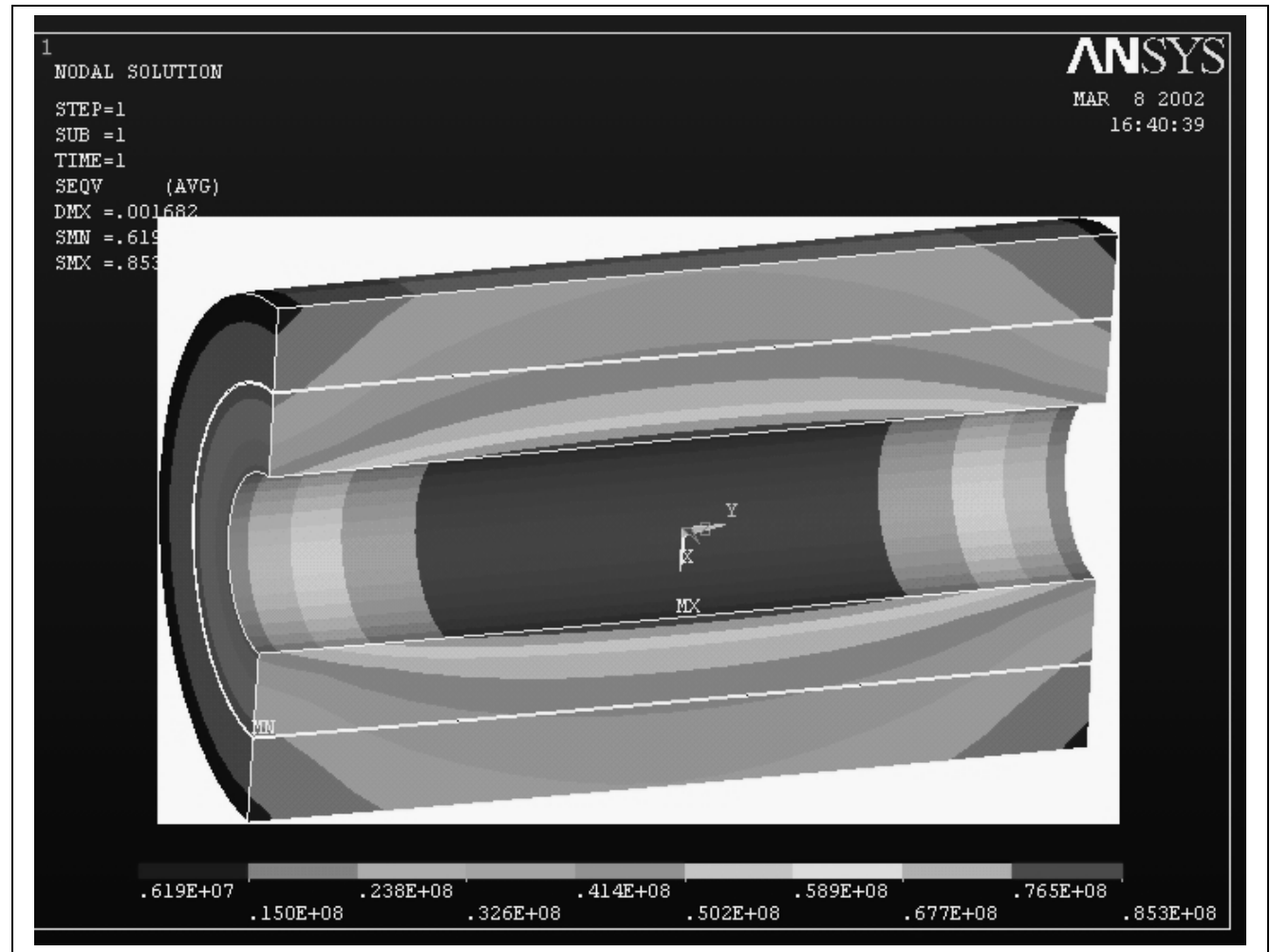




## Von Mises Stress Operating Mode 2, 10T

### Outer Segment Not Yet Installed

The max stress for this case is 85.3 MPa, which is a bit more than with the outer segment in place, but less than for the fully energized three segment coil





## Operational Thermal Stresses.

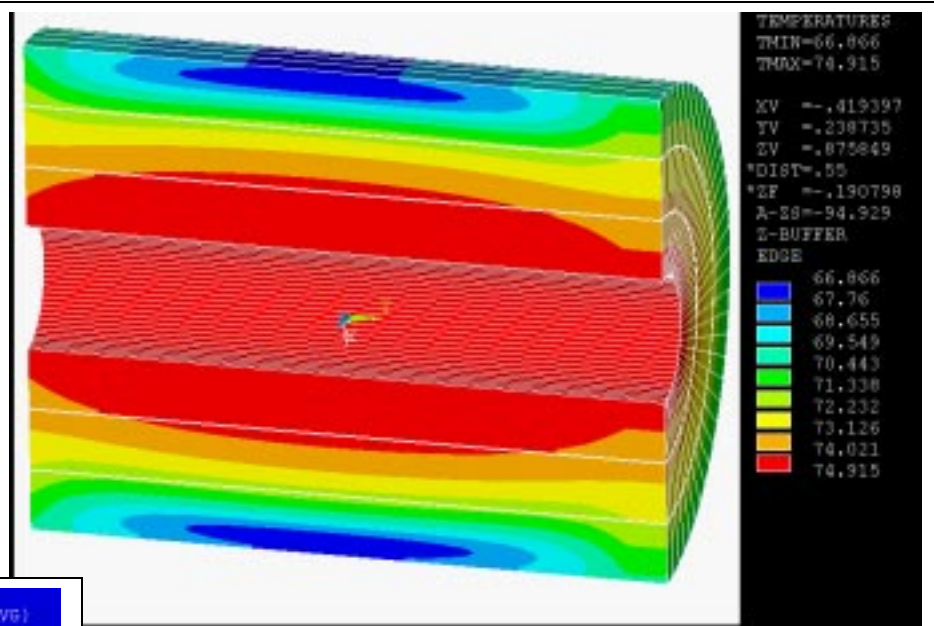
Although a constant current density coil, heat-up during a pulse is not uniform due to the magneto-resistive effects.

Temperatures were calculated for the 15 sec ramp-up, and 2 sec flat top and a 7 sec ramp down. The NIST Kohler plot and fitted equation was used for the magneto-resistance.

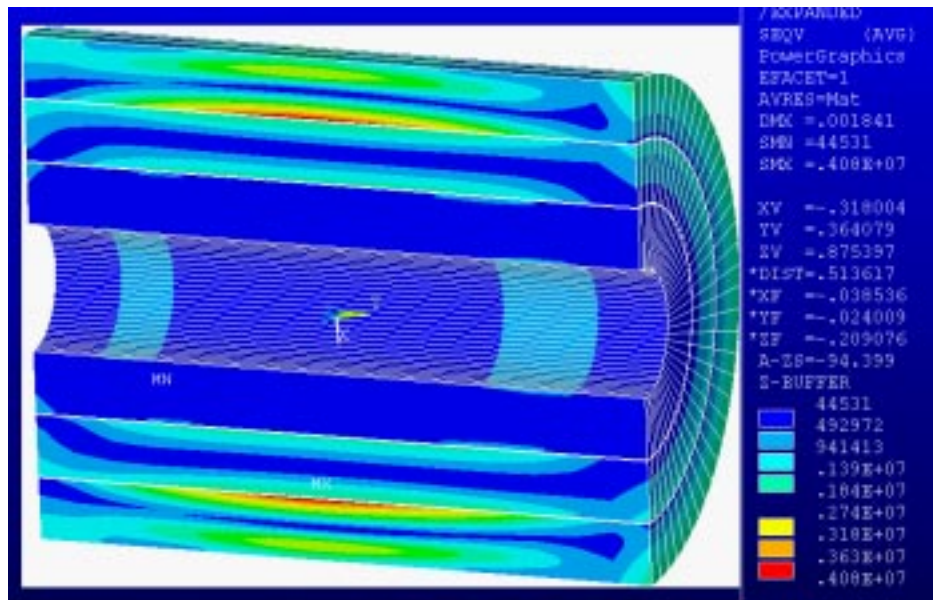
In my calculations, the temperatures were low compared with Bob Weggel's. The difference was the conservatism the Bob applied to his analysis from the scatter of the Kohler plot.

To make some progress on the stress calculations I stretched the time scale to come closer to Bob's temperature distribution.

The stresses from this analysis are small, less than 5 MPa.



Temperatures with magneto-resistive effects, 14.5T

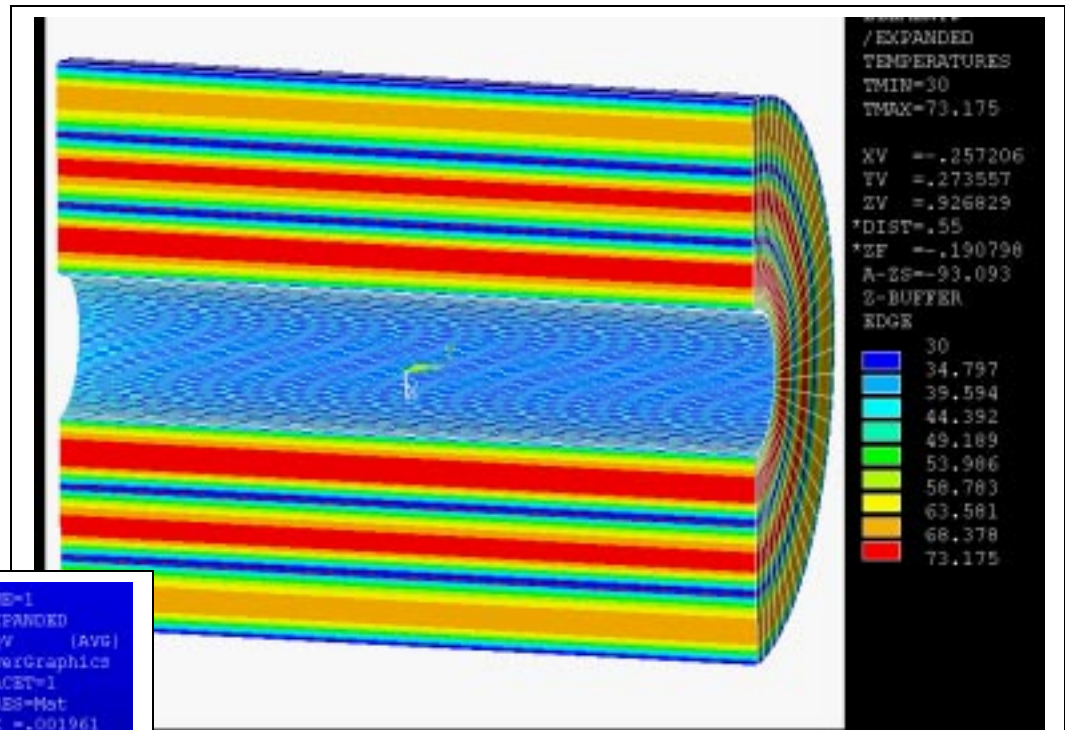


Resulting VonMise Stresses due to Temperature including the magneto-resistive effects, 14.5T.

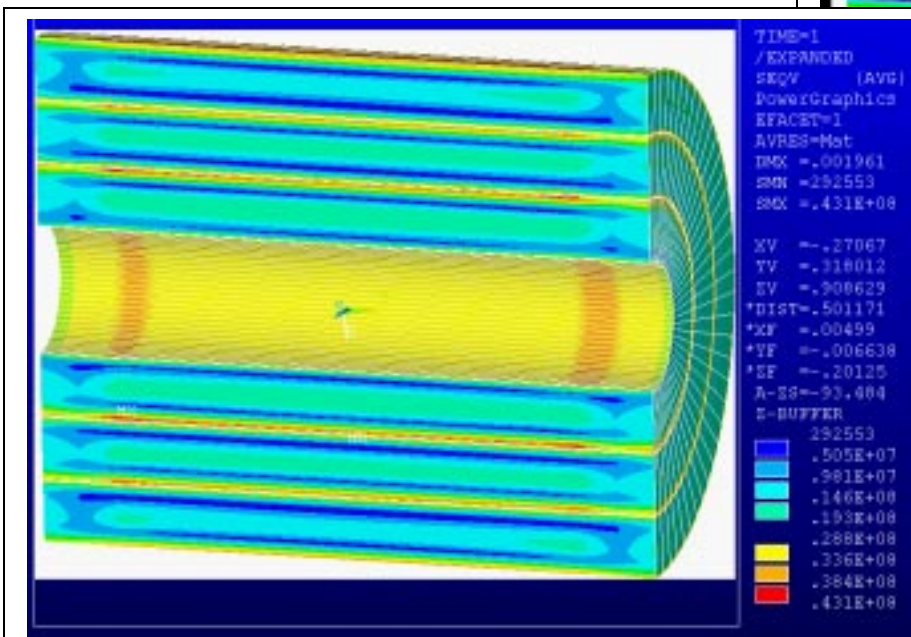
## Cooldown Stresses – Von Mises

The channels were held at 30K and the temperature distribution was obtained by averaging nodal temperatures with the final temp distribution from the heat-up calculations. This is not rigorous, and is essentially assumed, but it is representative of temperature distribution, and will serve to provide guidance for further analysis and design.

**The VonMises stress is relatively modest, at 43MPa**



Cooldown Temperature distribution



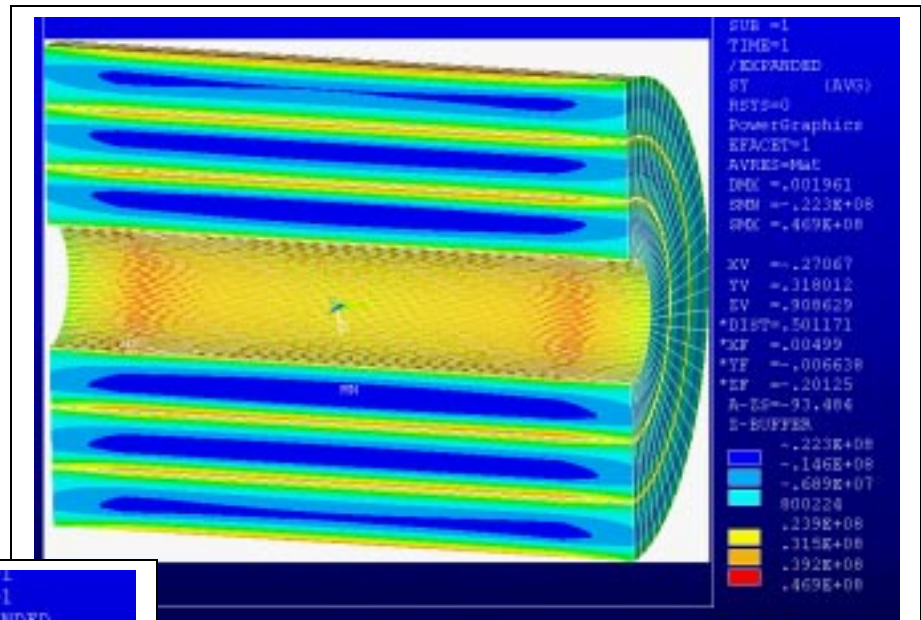
“Smeared” VonMises stress



## Cooldown Stresses –Shear and Axial Tension

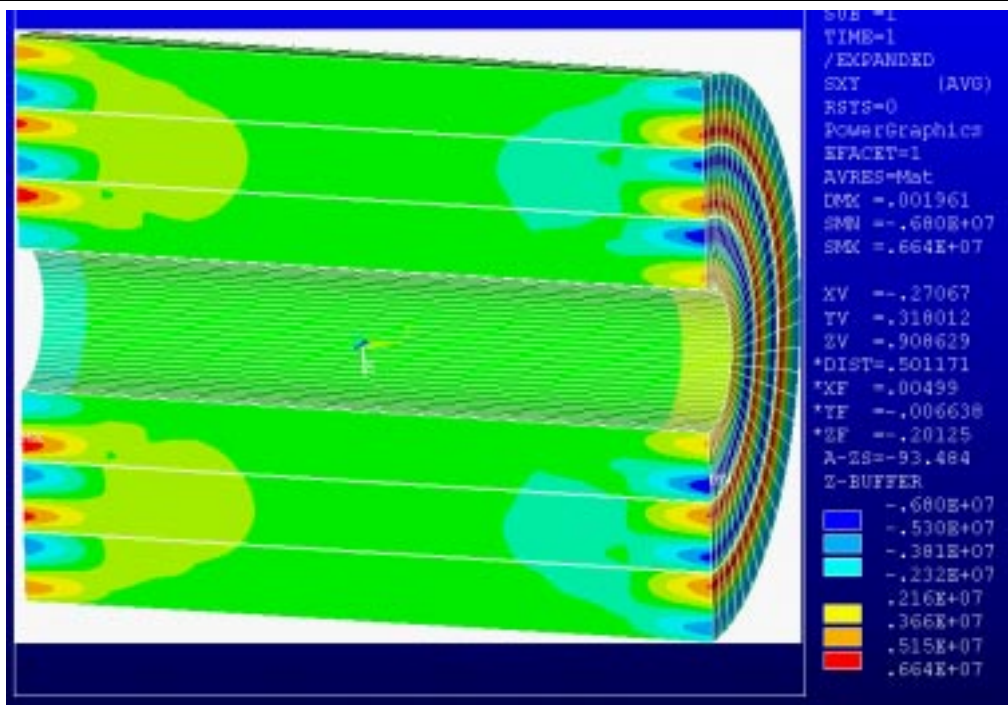
The axial tension near the channels is approaching 50 MPa, beyond the design capacity of epoxy bonded systems. Some provision will have to be made to either throttle the cooling gas to limit the channel temperature or design to allow the bond failure.

The shear stresses that peak at 7MPa are within the usual allowables for insulation systems, for which design allowables are in the range of 15 to 30 MPa (with no aid from compression)



Axial tension

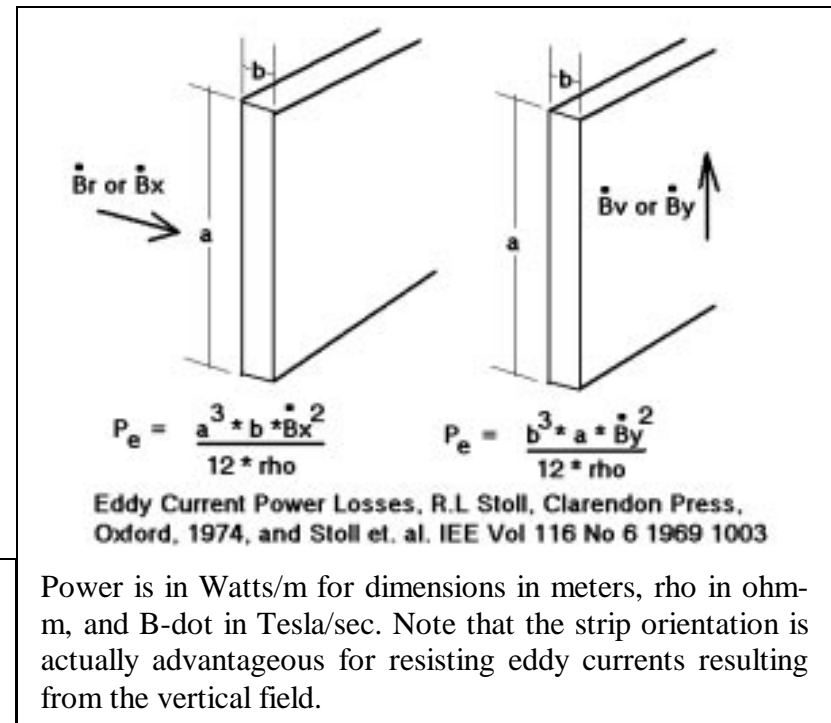
*The Axial Tension will be relieved with Kapton “Arcs” every eighth turn.*



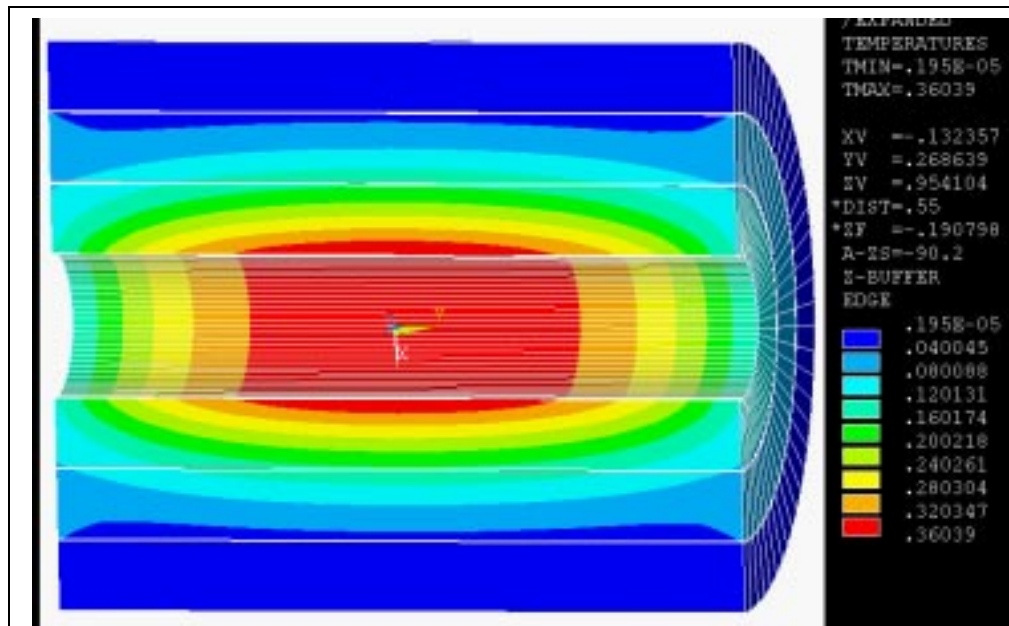
Shear stresses due to the cool down temperature distribution

## Eddy Current Temperatures – A Non-Problem

Transient fields induce eddy currents in the conductors as well as in the cryostat plates. This has been investigated for a strip wound solenoid used for FIRE, a fusion experiment. Eddy current heating has been evaluated for the BNL pulsed magnet using the same procedure. The conductor cross section is much lower for the BNL conductor, and the eddy current heating is less than one degree. – a non-problem.

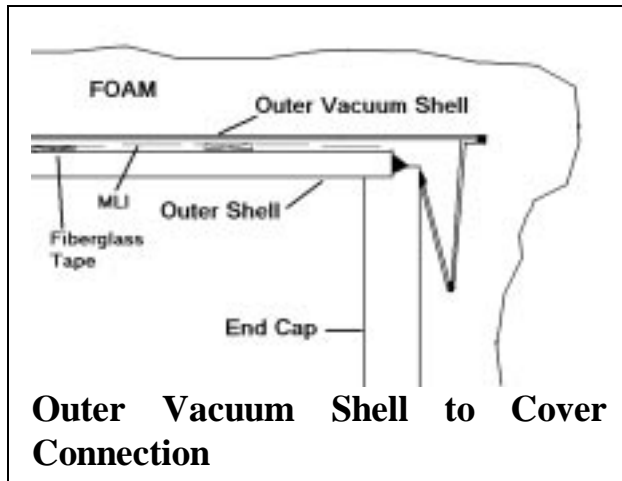


Power is in Watts/m for dimensions in meters, rho in ohm-m, and B-dot in Tesla/sec. Note that the strip orientation is actually advantageous for resisting eddy currents resulting from the vertical field.



Temperatures due to conductor eddy currents in .5in square conductors subjected to a 14.5T/7sec transient (rampdown)

## Steady State Heat Gain.

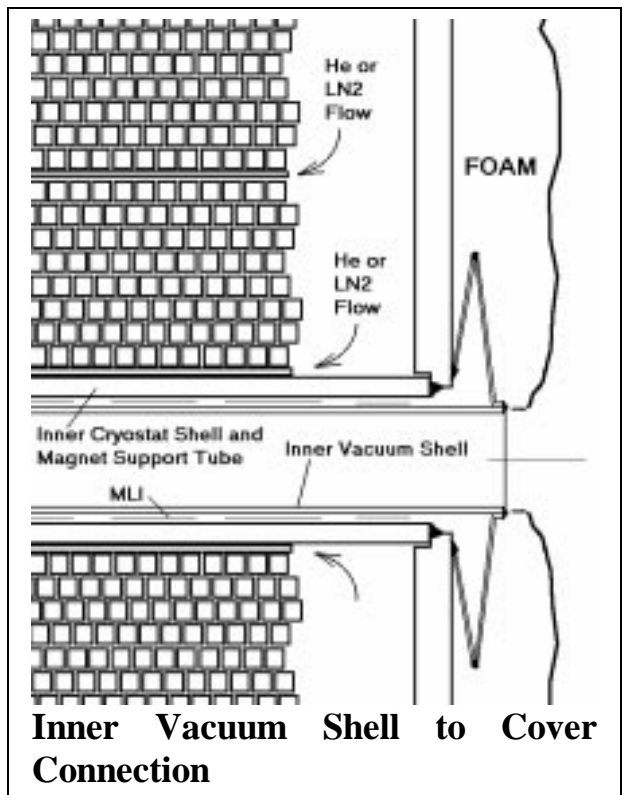


The specification requires that the cryostat heat gain should be  $<200$  W at 22 K Excluding the leads.

A concept which has a 220 watt heat gain has been developed that employs vacuum at one head, and the outer and inner shells, and foam at the other end around fluid and electrical penetrations.

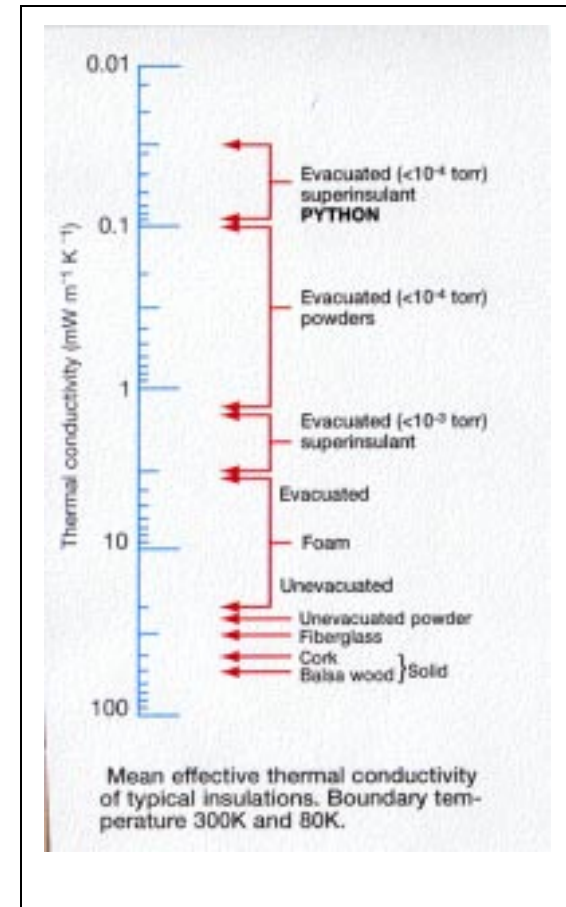
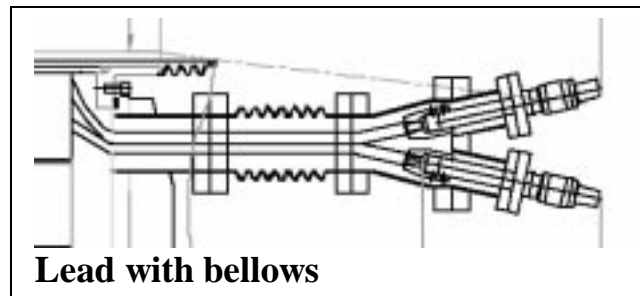
Piping penetrations are moved to the end plates,

Vacuum shells are used on the ID and OD, and one head.



The magnet can be supported off the inner cryostat shell,

The system gravity supports can reach through the foam or vacuum boundary.



## Heat Gain Summary

Component	Material	Thermal conductivity W/m/degK	Area m <sup>2</sup>	Length m	delta T	Heat rate watts
Inner shell vacuum with mli	Vacuum/MLI	*	.75398224	*	292-22	<20
Inner shell vacuum extensions	.0005m thick sst	16.27	6.283e-4	.2	292-22	13.8
Outer shell (foam option)	CTD Cryo foam insulation	.03	3.77	.1	292-22	303
Outer shell foam in series with vacuum+mli	CTD foam insulation	.03		.1	292-220	49**
Outer shell Vacuum Extension	sst	16.27	3.14159e-3	.2	292-220	18.4
End Cover foam (1 end)	CTD foam insulation	.03	1.508	.1	292-22	62.85
End Cover	Vacuum +mli					
Leads	Copper (22 to 80K)	396.5	8.64e-4	.4	80-22	49.6 (3 pairs)
Leads	Copper (80 to 292K)	396.5	5.4569e-4	.4	292-80	114.7 (2 pairs)
Lead bellows	sst	16.27	4.7124e-4	.4	292-22	5.33
Coil Support pads	g-10	.15	.0016	.05	292-22	1.296
Total bold red						220.

\* Radiation heat gain at bore= 37.281177 watts (no MLI) Stefan Boltzman Constant =  $5.668 \times 10^{-8}$  watts/m<sup>2</sup>/degK<sup>4</sup>  $q_{rad} = \text{area} \times \text{emis} \times \text{stefboltz} \times (\text{trt}^4 - \text{tcold}^4)$ , emis=.12 polished sst From ref [8]: page 152. the heat flux should be divided by the number of MLI layers, conservatively it was divided by 2 – many more layers are practical in this space.

\*\* Radiation and Foam conduction in series. The intermediate temperature (128.5K) of the vacuum shell was found by trial and error assuming a temperature and matching the heat flux for radiation and conduction.

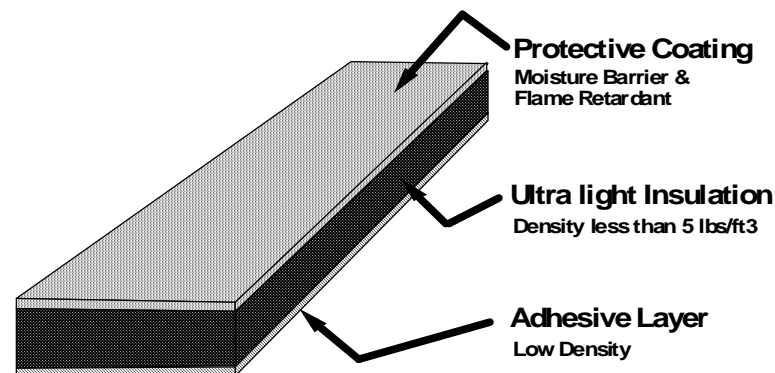
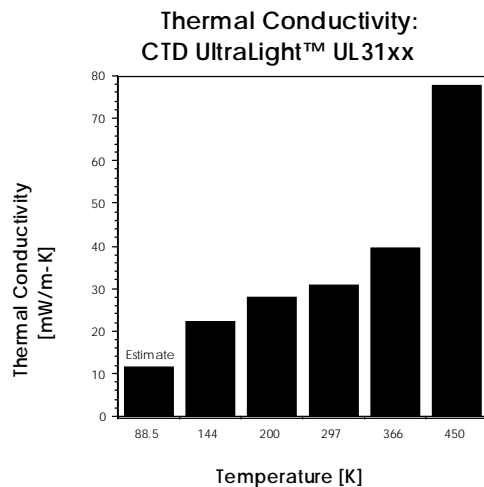
# Foam Insulation

## CTD Composite Technology Development Inc.

**CryoCoat™ 620T** was initially developed to prevent the formation of liquid air on ground-based **liquid hydrogen vent lines**, and has since found numerous applications as an insulation, adhesive, sealant, protective coating, and grout for ground-based and flight applications. CryoCoat™ 620T offers excellent adhesion to many substrates with minimal surface preparation, and will cure at temperatures as low as 10°C in 8 hours. These characteristics make it especially attractive for retrofit and field installations. Known for its robustness and toughness, this syntactic foam-based insulation is resistant to UV and other environmental factors, and **does not absorb moisture**. It can be **spray applied** to large surface areas, complex surfaces, and difficult to reach areas.

**CryoCoat™ UltraLight™** provides the robust mechanical properties associated with syntactic foam technology in a low-density insulation system (specific gravity from 0.08 to 0.11) with excellent thermal properties. CryoCoat™ UltraLight™ can be used as a mold-in-place insulation system on large, complex and uneven surfaces, or blown into closed molds to form near-net-shape components. CryoCoat™ UltraLight™ UL79 withstands liquid hydrogen temperatures and the elevated temperatures of re-entry from space.

The CryoCoat™ UltraLight™ consists of an adhesive layer, an insulation layer, and an outer moisture barrier/protective coating. Each component can be individually tailored to best meet the requirements of a specific application. For example, for use on a cryogenic fuel tank or rocket engine hydrogen pump, the adhesive layer will use CTD's CryoBond™ 920 adhesive, and the outer coating will be based on CTD's CryoBond™ XVC. The outer coating can be omitted in applications where the insulation will be exposed to a vacuum, improving the overall insulation effectiveness. The outgassing of UL-79 is low enough to maintain a stable vacuum. In applications where the insulation will be formed into a near-net-shaped part, or used on equipment requiring access for maintenance, the adhesive can be eliminated. This will allow easy removal of the insulation. CryoCoat™ UltraLight™ adheres well to itself, enabling easy insulation repair or replacement.





## Cryostat/Helium Can Stress

Normal operating Pressure is 15 atm – May “evolve” depending on ballast tank

Flat head thickness is 2 cm.

ID and OD shell thickness is 6.35mm (1/4 inch) (present analysis is based on 5mm)

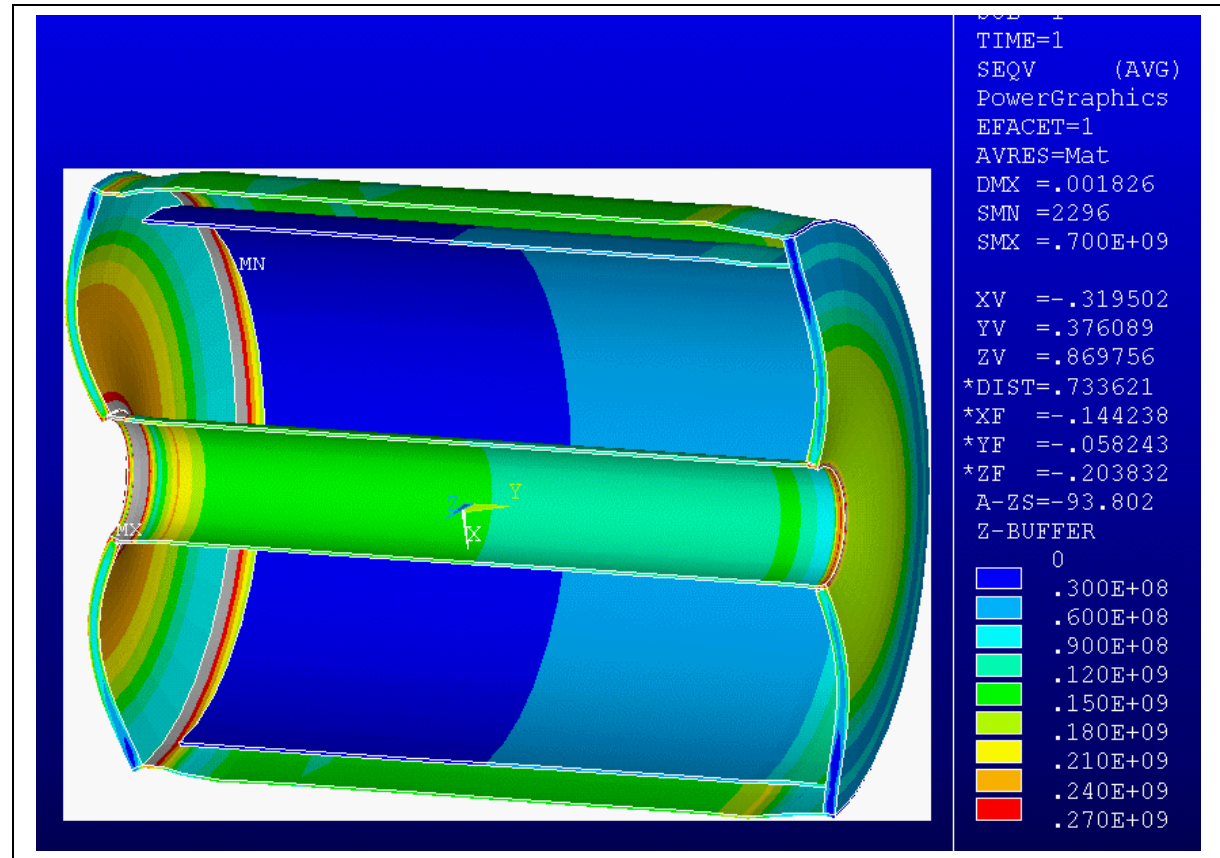
Material is 316 or 304 SST

Structure Room Temperature (292 K)

Maximum Allowable Stresses,  
 $S_m$  = lesser of 1/3 ultimate or  
2/3 yield, and bending  
allowable =  $1.5 \cdot S_m$

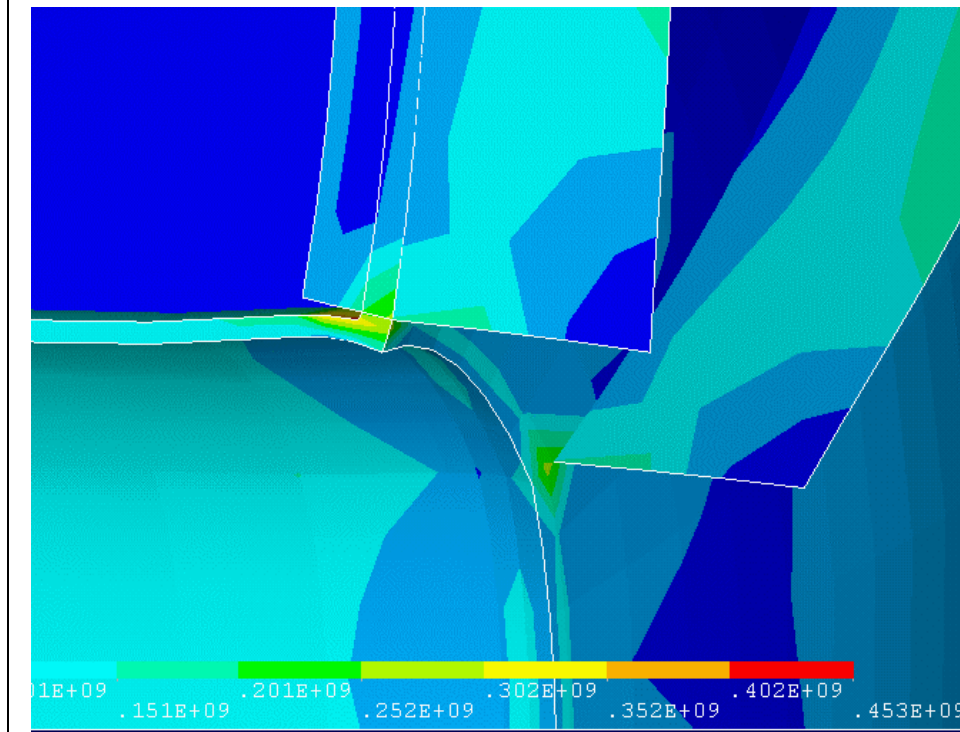
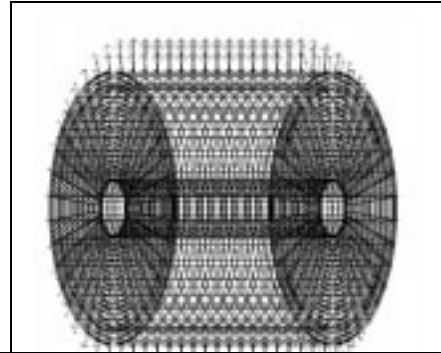
Material	$S_m$	$1.5S_m$ – bending
316 LN SST	183Mpa (26.6 ksi)	275Mpa, (40ksi)
316 LN SST weld	160MPa (23.2ksi)	241MPa (35ksi)

**Local (corner) Stresses were high - 700 MPa. Stiffeners or thicker closure heads were specified to protect the seal welds**

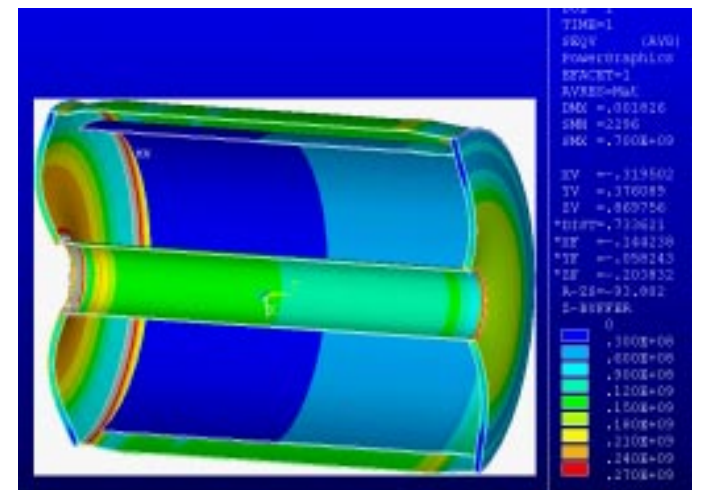


## Cryostat/Helium Can Stress – Head Closure Detail

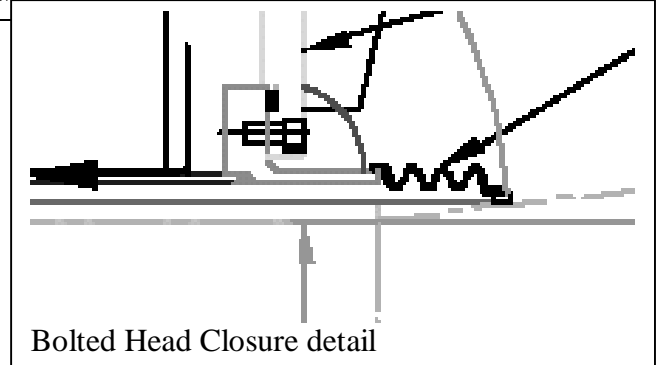
Without stiffeners on the flat head, local corner weld stresses are high - 700 MPa. After the addition of six 1cm thick stiffener ribs, the peak stress went down to 448 MPa. This occurred in the ribs, and the weld and head stresses are much improved, but are still above 300 MPa. Further reductions are needed to meet the weld allowables, although the plate allowables summarized above are for room temperature, and are much below the cryogenic capability of 304 or 316.. Increasing the depth of the ribs from the 6cm modeled, is indicated



Local stress in the shell to head weld. 6cm high, by 1cm thick ribs are modeled. – Consider 2cm thick



VonMises Stress without ribs



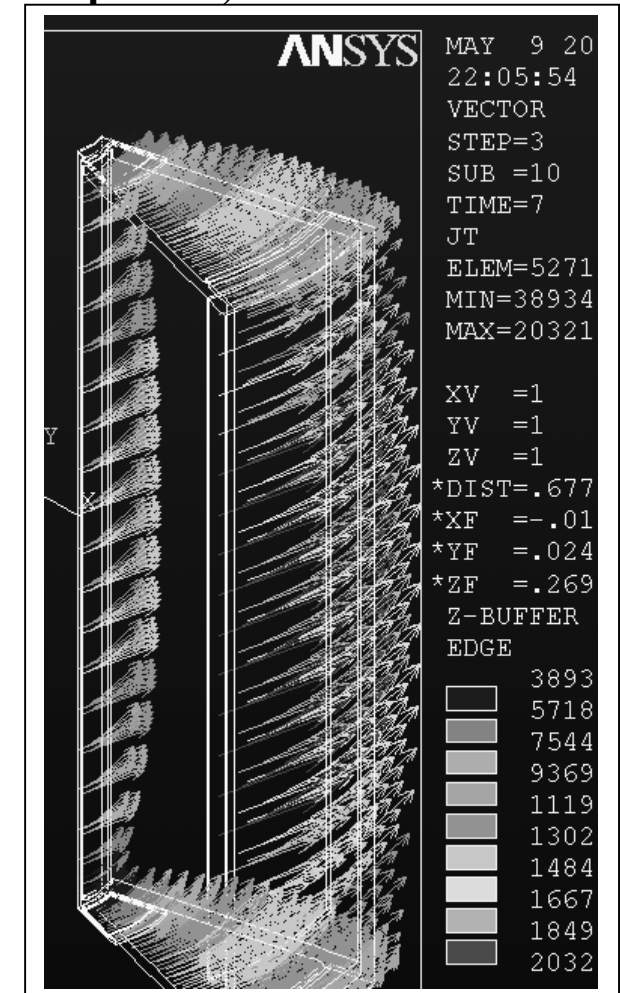
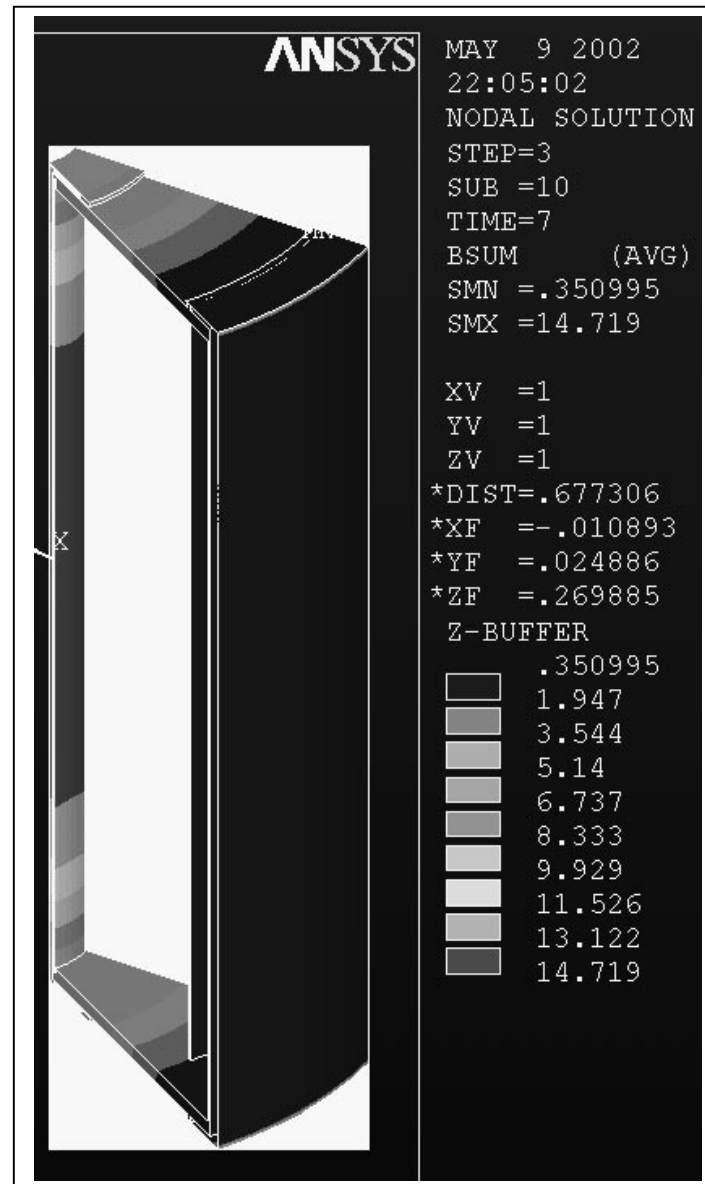
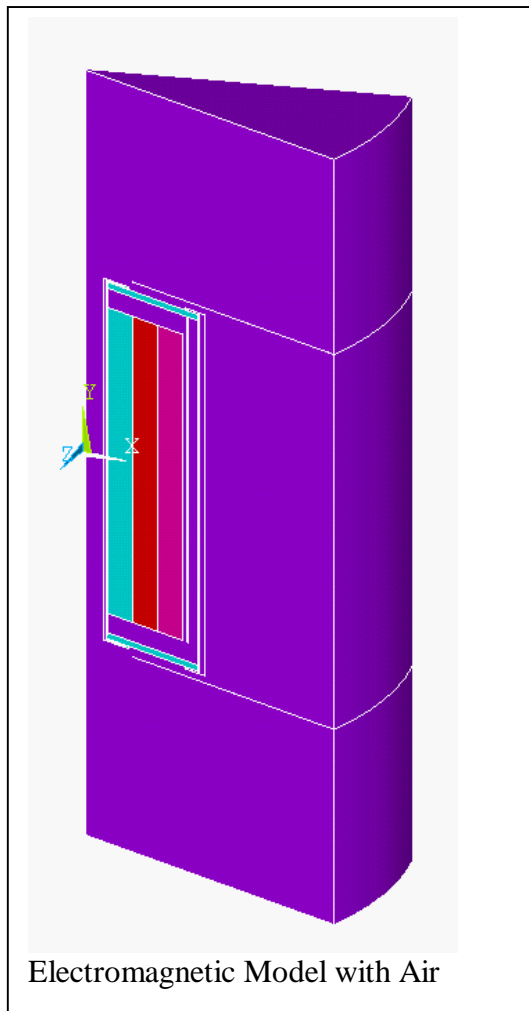
Bolted Head Closure detail

*Local Detailed Analysis is planned*

## Cryostat Eddy Current Analysis

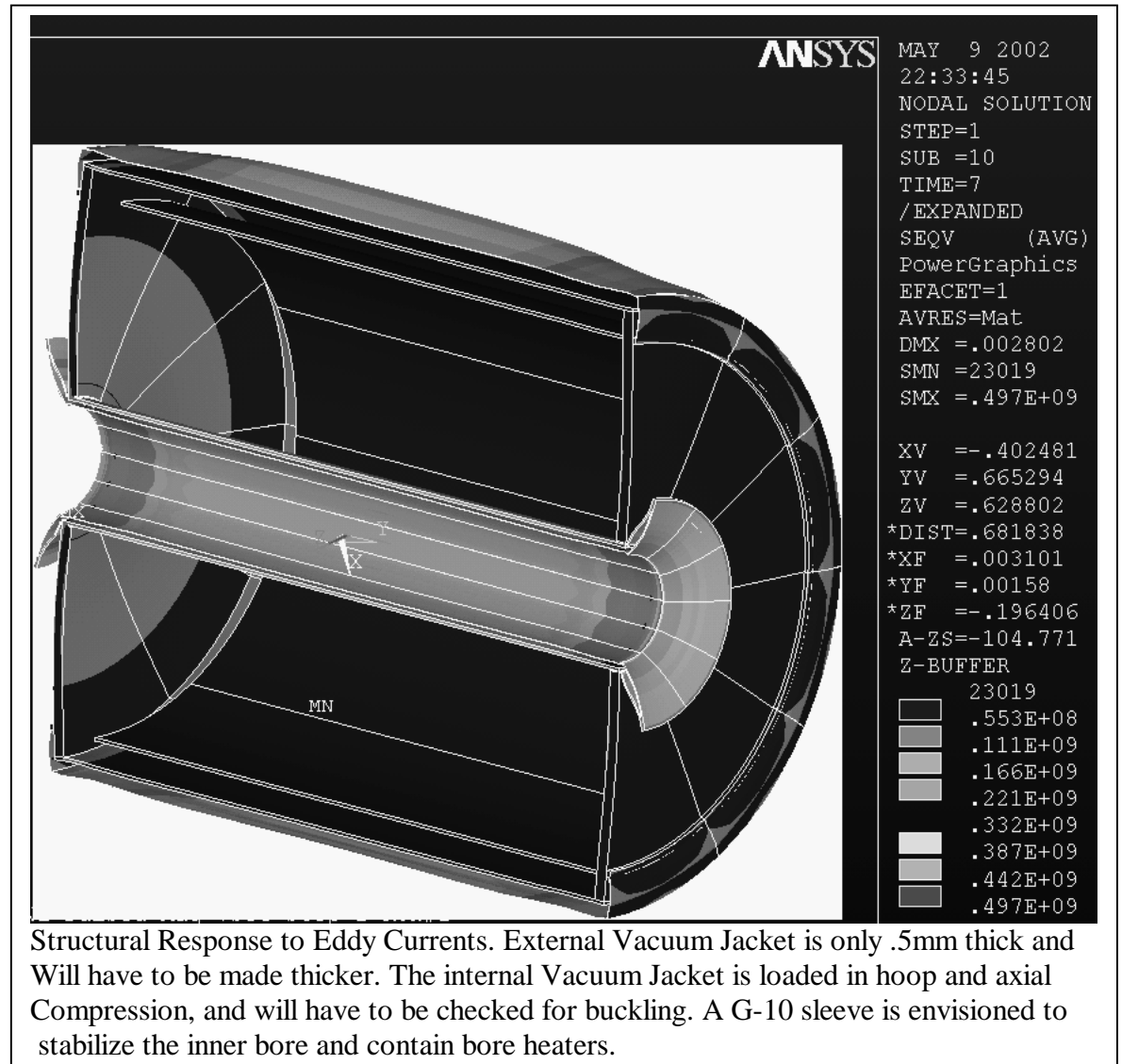
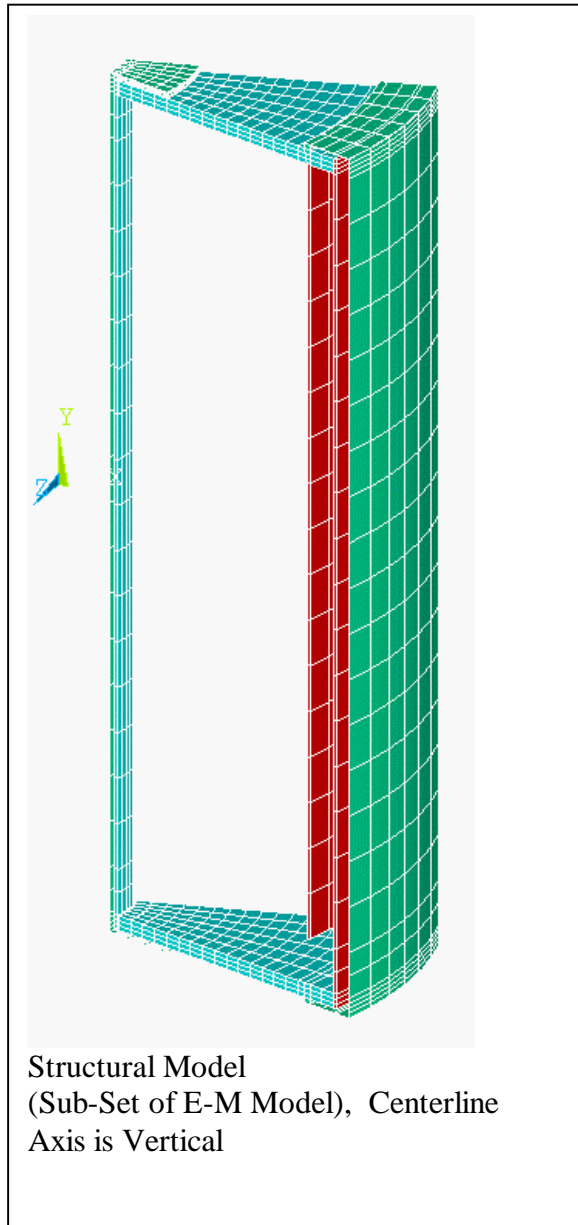
**Vector Potential Solution, 7 sec Ramp-Up , (Envelopes ramp-up and ramp down)**

**Field Loss Due to Eddy's is  
of the Order of a few  
milliTesla**



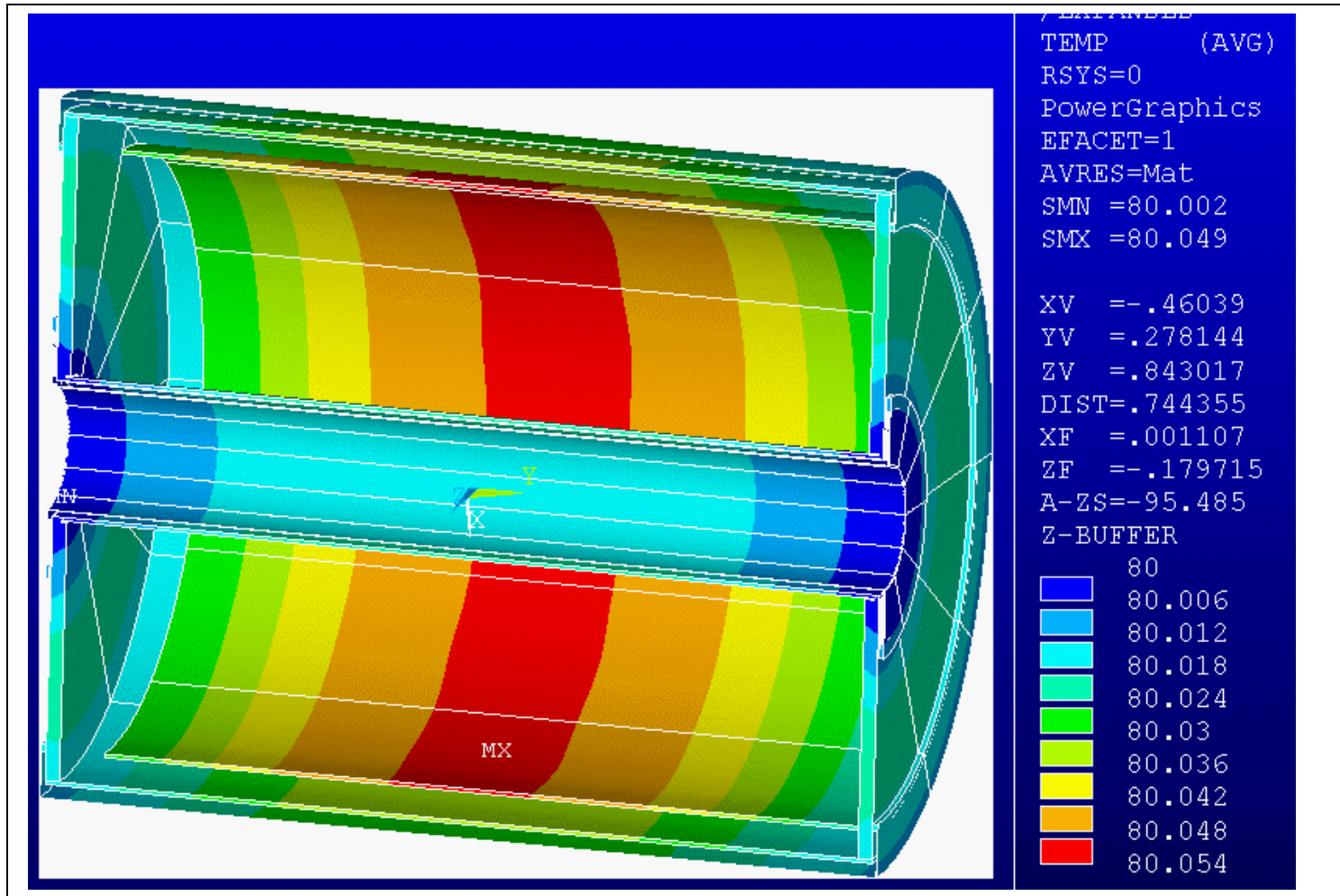


## Cryostat Eddy Current Analysis – Will be updated with Dished Head



## Cryostat Eddy Current Analysis – Temperature Pass

Heat-up due to the eddy current loading on the cryostat produces less than 1 degree K

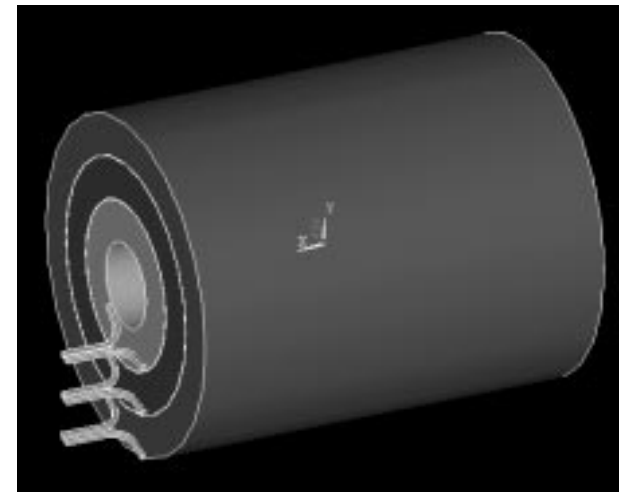
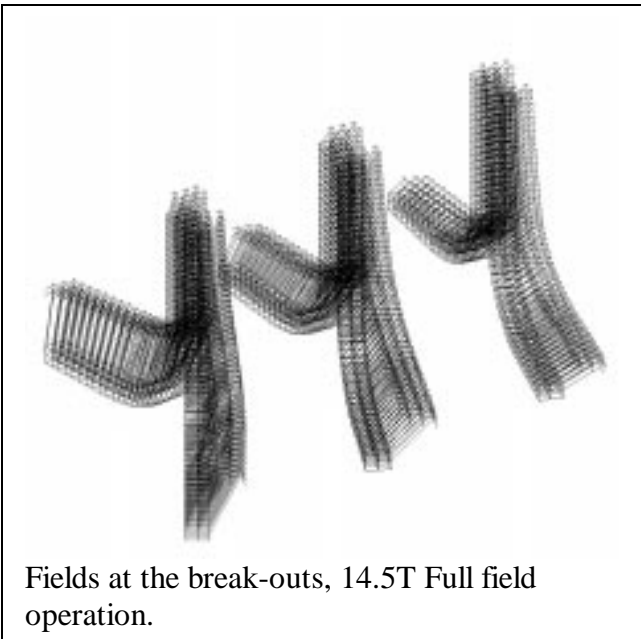


***Planned:***

***Addition of  
Buckling  
Analysis –  
Use Load  
Vector from  
Stress Pass.***

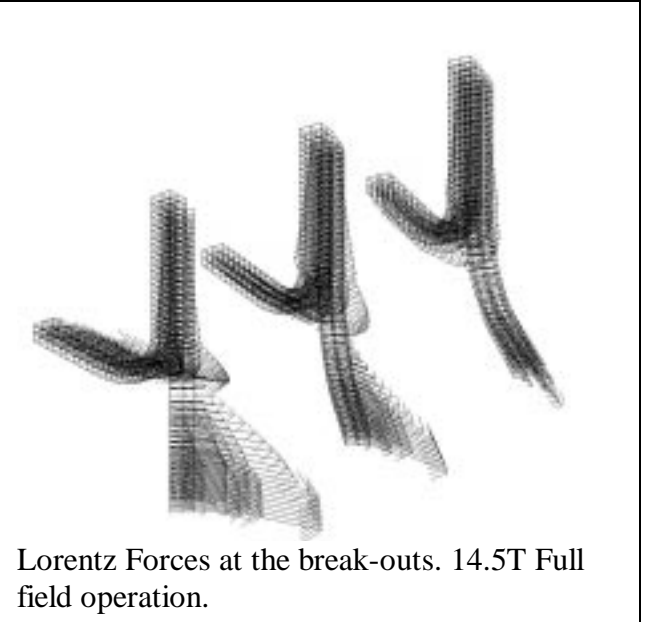
## Break-Outs, Leads, and Penetrations

- The choice of modular design favors duplicating the break-out and lead design for all three segments, even though two of the segments are connected in series.
- The break-out concept structurally connects the inner layer break-out with the outer layer break-out.
- The leads are closely coupled to cancel the net loads on the lead conductors.
- Loads cancel, but there is a small torque.
- To achieve the interconnection of the leads, they cross the face of the winding.
- Bending stresses for combined thermal and Lorentz force loading of 200 MPa can be expected for the cantilevered leads. The analysis model has minimal fiberglass wrap and more extensive interconnection of the leads, and support at the winding pack end will be needed.

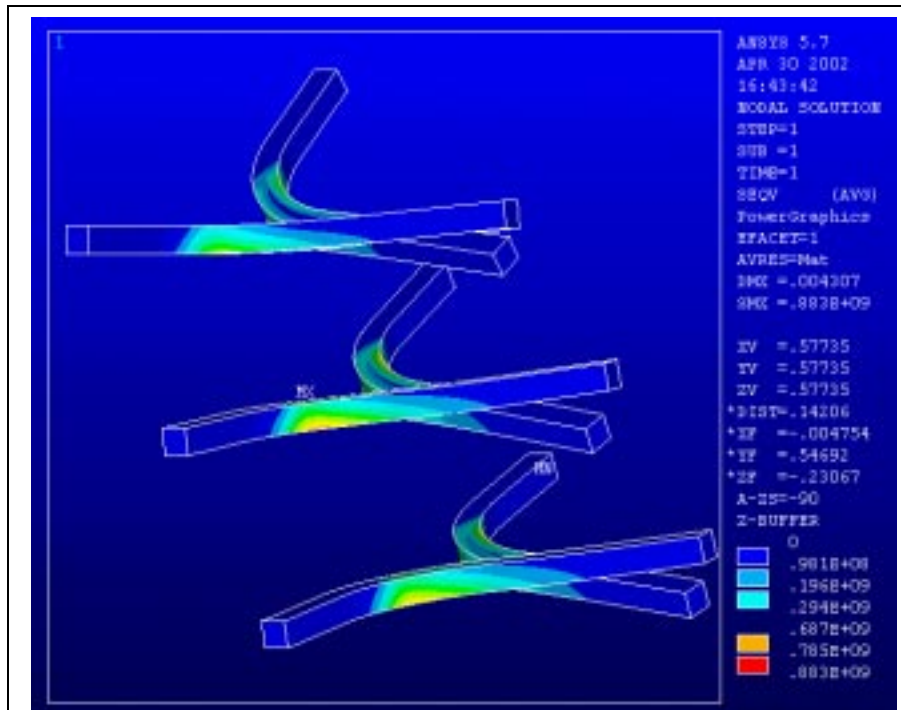


The electromagnetic model.

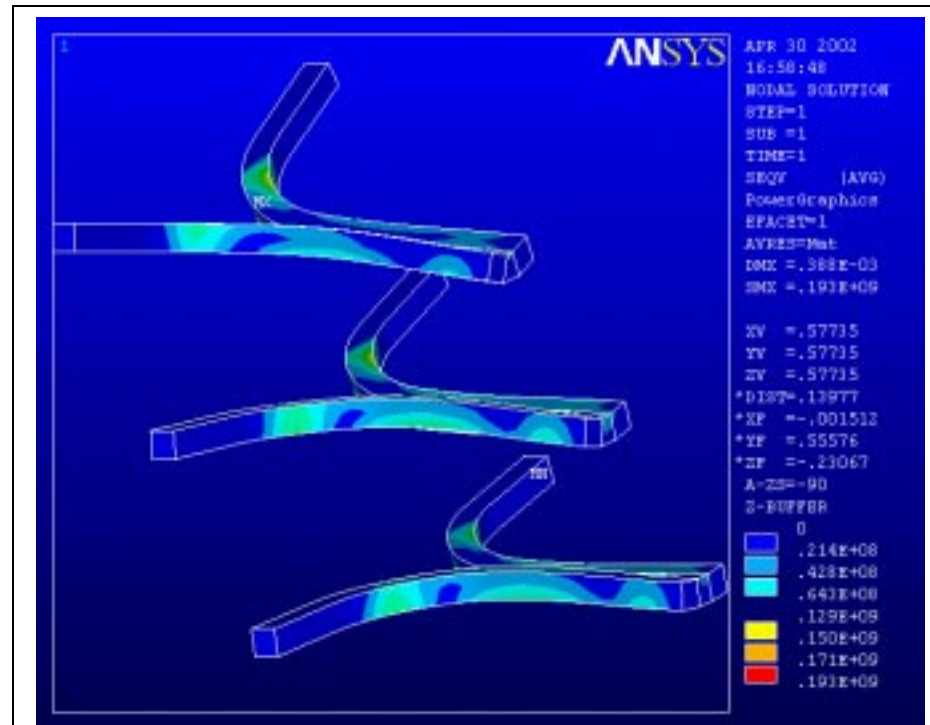
The fields and forces in the leads are calculated with 7200 amps in the leads, and the appropriate solenoid end field solution is



## Break-Outs are Interconnected to Cancel Loads, and Equilibrate Hoop Stress.



Winding ends well supported, Terminal ends Un-supported and not interconnected. Lorentz Forces Only

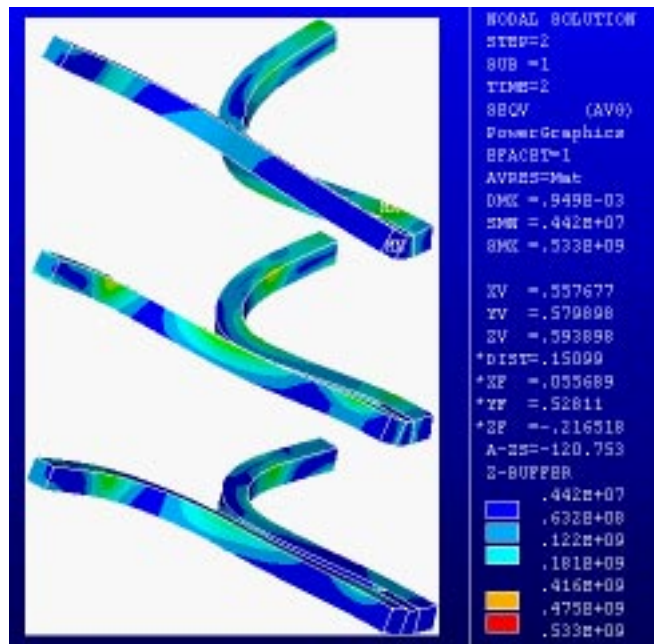
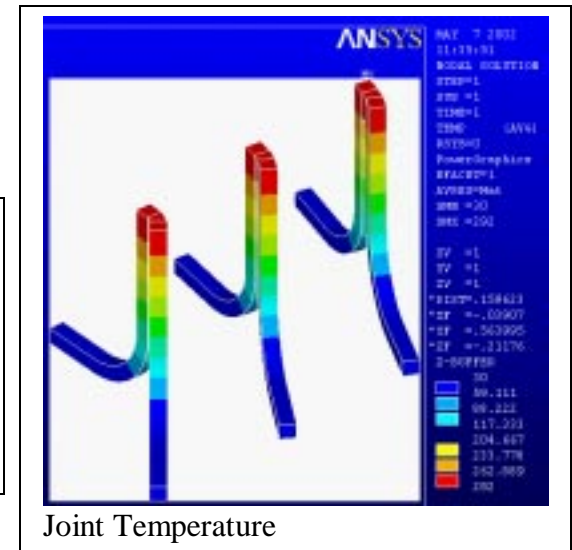
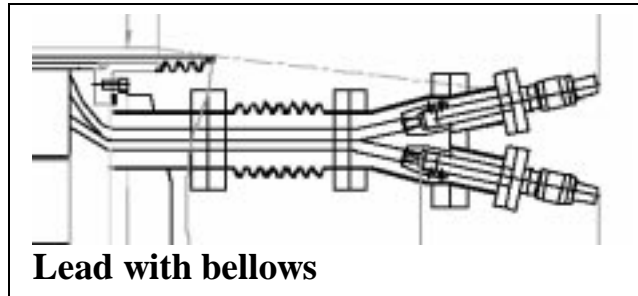


Winding ends well supported, Terminal ends interconnected at the end of the lead pair. Lorentz Forces Only

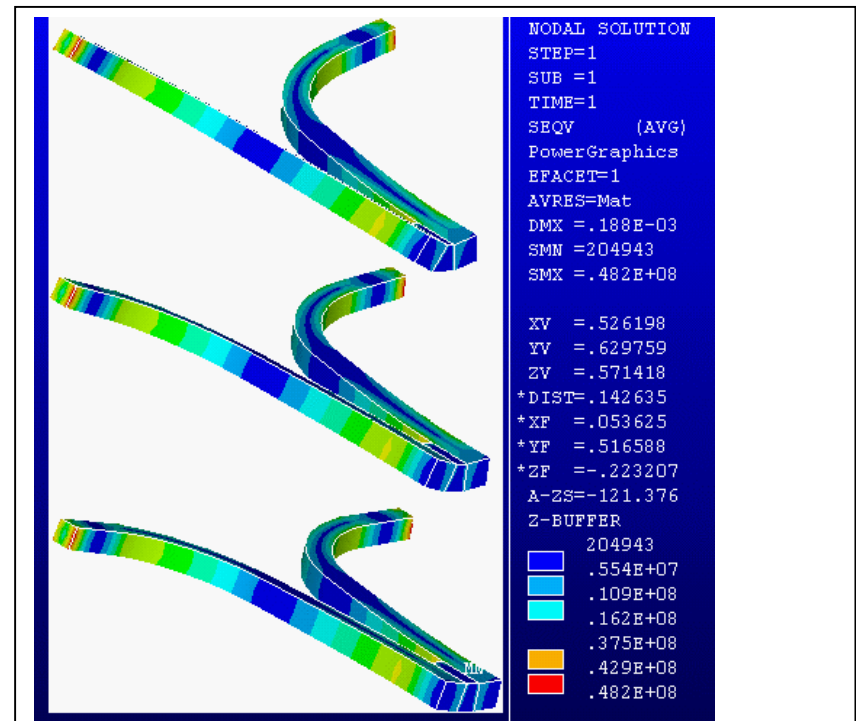


## Lead Thermal Stresses

- A bellows is used because of differential thermal motions, and flexure of the end cap under pressure loading
- This also has the effect of lengthening the cold length of the lead, reducing the heat gain.
- A conduction solution is used to obtain the temperature gradient for the structural solution



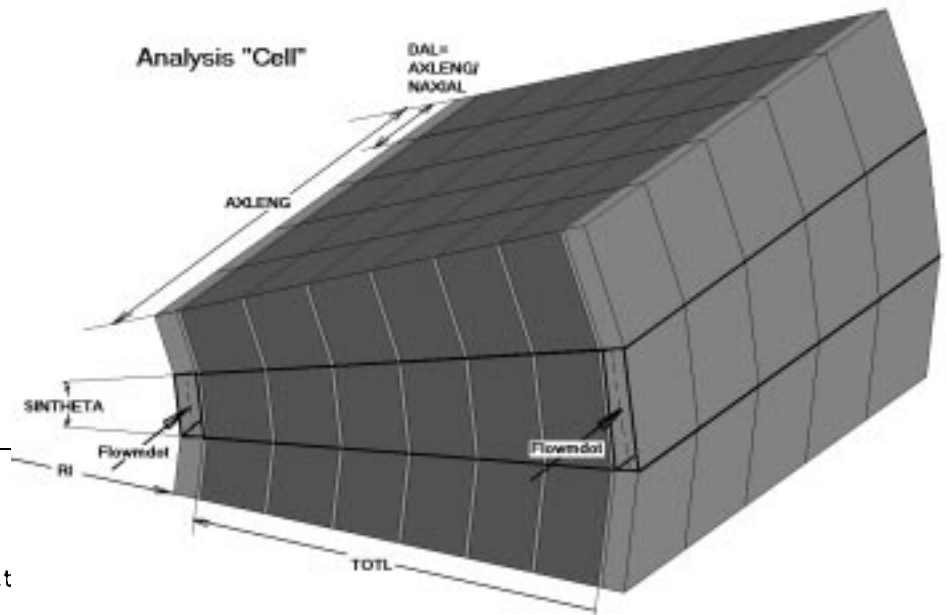
Thermal+Lorentz stress. Winding ends well supported at extreme of the radius, where the thermal constraint was applied. The peak stress occurs where the relatively short interconnection ends. This will be lengthened, and will reduce the peak stress.



Joint thermal stress. Winding ends well supported at extreme of the radius, where the thermal constraint was applied



**Cooldown Calculations:  
Finite Difference Model is Used.  
Channel Flow and  
Transient Heat Conduction  
Reducing the Kapton between Layers Allows  
8 layers to be cooled from axial channels.**



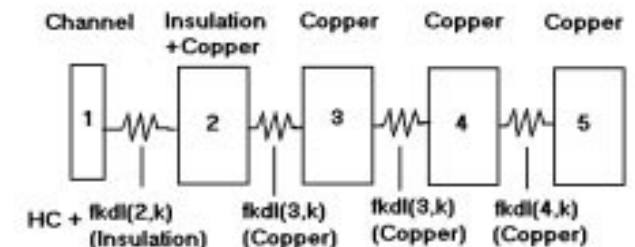
**2.1.3 Convective Heat Transfer**

It is important to estimate how much heat the superheat gas ( $T > 77$  K) could absorb before exiting the cooling channel. The convective heat transfer coefficient,  $h$ , could be obtained from

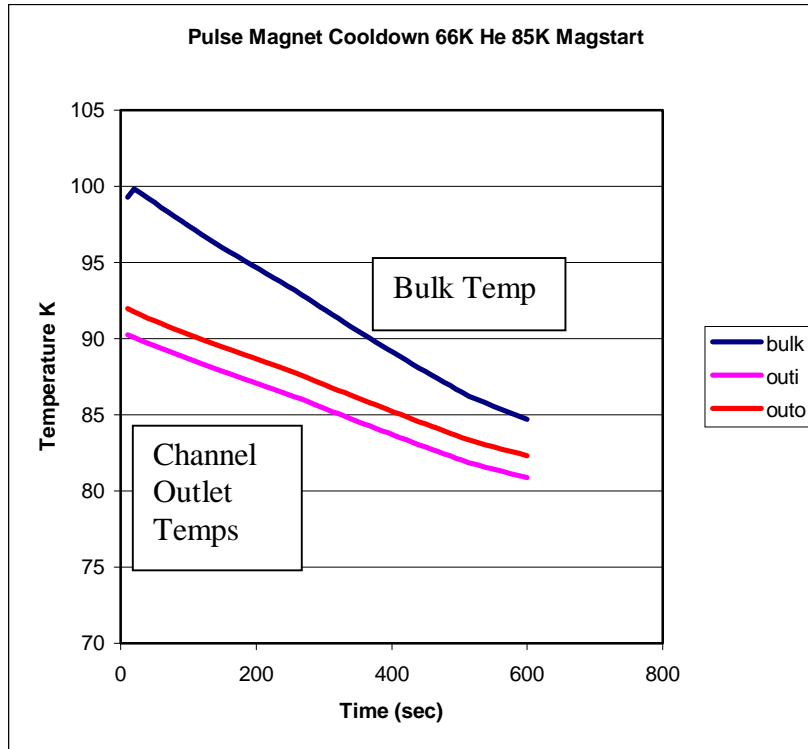
$$h = \frac{K \text{Nu}}{D_e} = \frac{0.023 \text{Re}^{0.8} \text{Pr}^{0.4} K}{D_e} \quad (14)$$

This coefficient is about  $21 \times 10^{-3} \text{ W/cm}^2 \text{ K}$  at a vapor temperature of 200 K, vapor velocity of 40 m/s, and hydraulic diameter of 2 cm. It drops to  $17 \times 10^{-3} \text{ W/cm}^2 \text{ K}$  at a vapor temperature of 100 K, keeping the mass flow rate constant. It is interesting to note that the heat transfer coefficient for film boiling at 200 K from Fig. 4 is about  $12 \times 10^{-3} \text{ W/cm}^2 \text{ K}$ , which partially justifies the third assumption in Sect. 2.1.

excerpt from: ORNL/FEDC-85-10 Dist Category UC20 c, dated October 1986



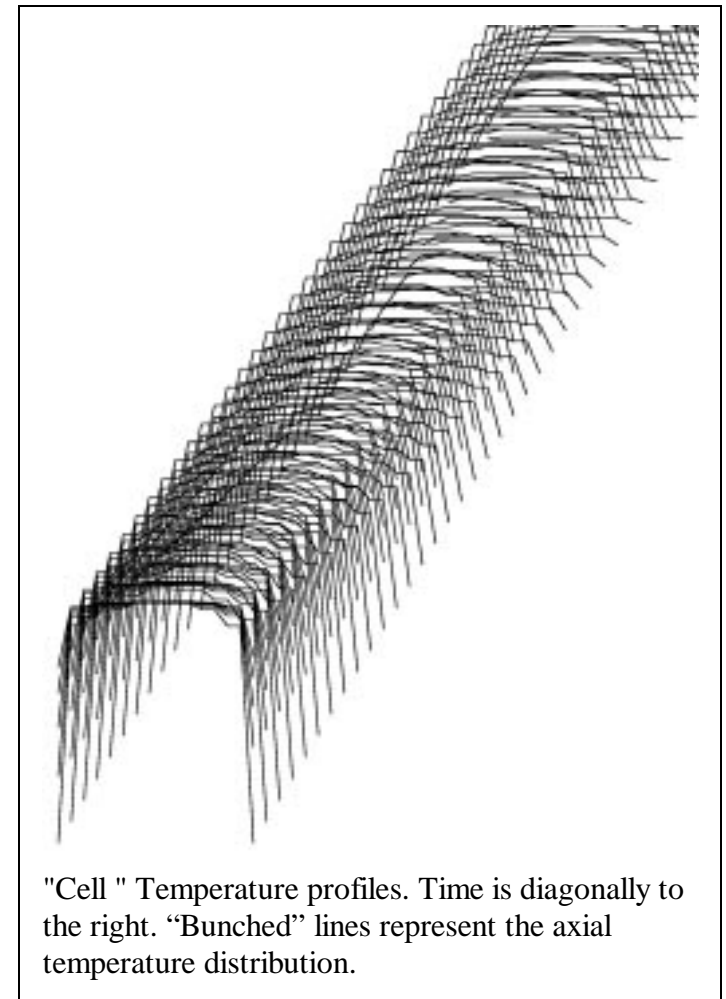
Channel Edge Thermal Model



66K inlet temperature, Time Step = .0001 sec – 100 K after Pulse Temp, The bulk temp is computed at a mid -axial slice. Time to 85K is about 600 sec or 10 min. Exclusive of time to flatten temp distribution.

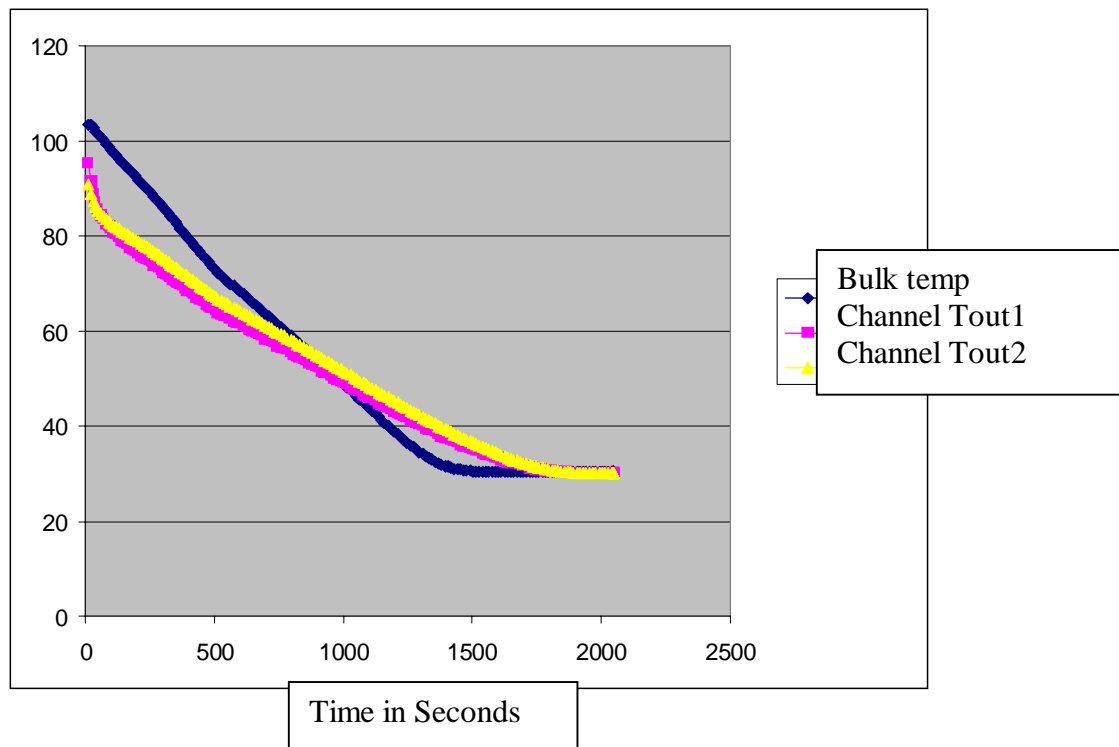
#### Present Operational Scenarios:

Case #	Peak Field	T after pulse	T coolant	Start Bulk Temp	Guestimated Time	Guestimated Time
1	5T	90K	66K	84K	~200 sec	3.3 min
2	10T	96K	66K	74K	~800 sec	13.3 min
3	14.5T	78K	22K	30K	~1500 sec	25.0 min





## 30K Coolant, Cooldown from 100K



Bulk Temp Is Computed Mid Axial Build - It Bottoms out before the down stream end.

tout 1 and tout2 are Outlet Temperatures

Analyses to date: Time to target bulk temp. ½ inch Copper Conductor, 100K ,

	T after pulse	T coolant	Cond Layers	Time to 85K sec	Time to 30K sec
Equiv 5 Kapton .001in wrap	100K	66K	6 layers	600	
Equiv 5 Kapton .001in wrap	100K	66K	8 layers	>850	
Equiv 3 Kapton .001in wrap	100K	66K	8 layers	450	
Equiv 5 kapton .0001in wrap	100K	30K	6 Layers		2000







## Assembly and Manufacture

**The Coil is layer wound**

**The Coil is made in three segments. Phased manufacture is allowed**

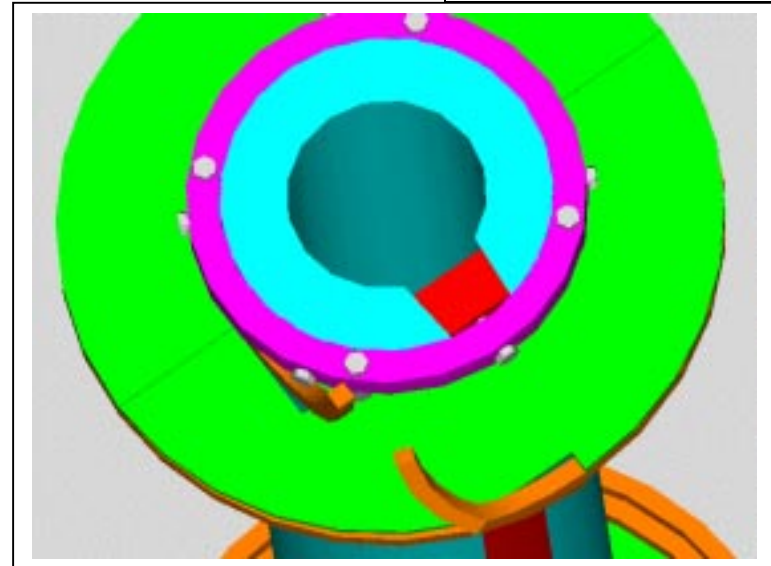
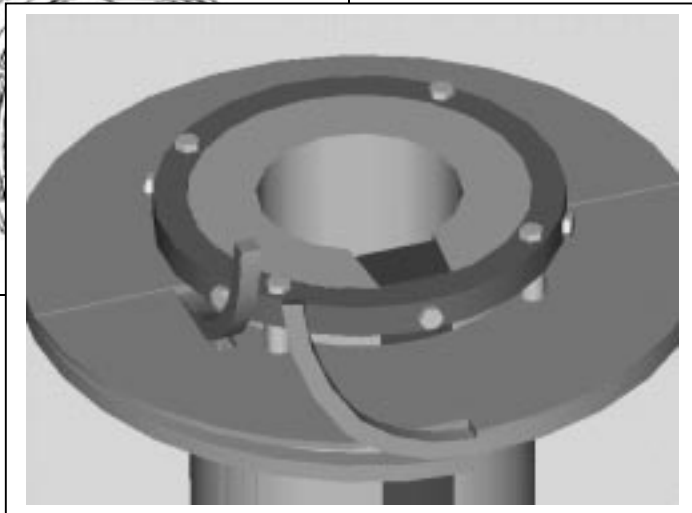
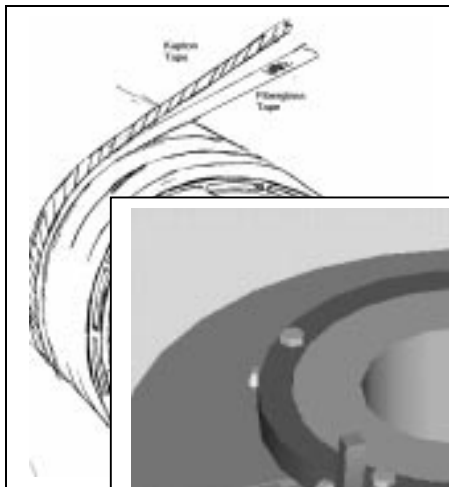
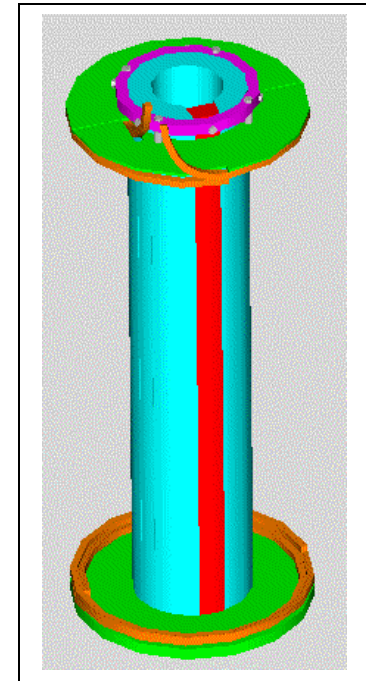
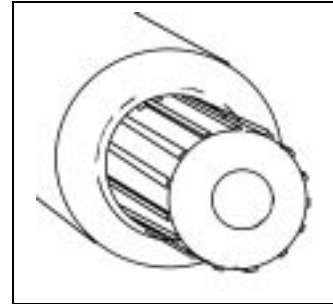
**Three separate mandrels are planned.**

**Mandrels maintain a precise bore geometry**

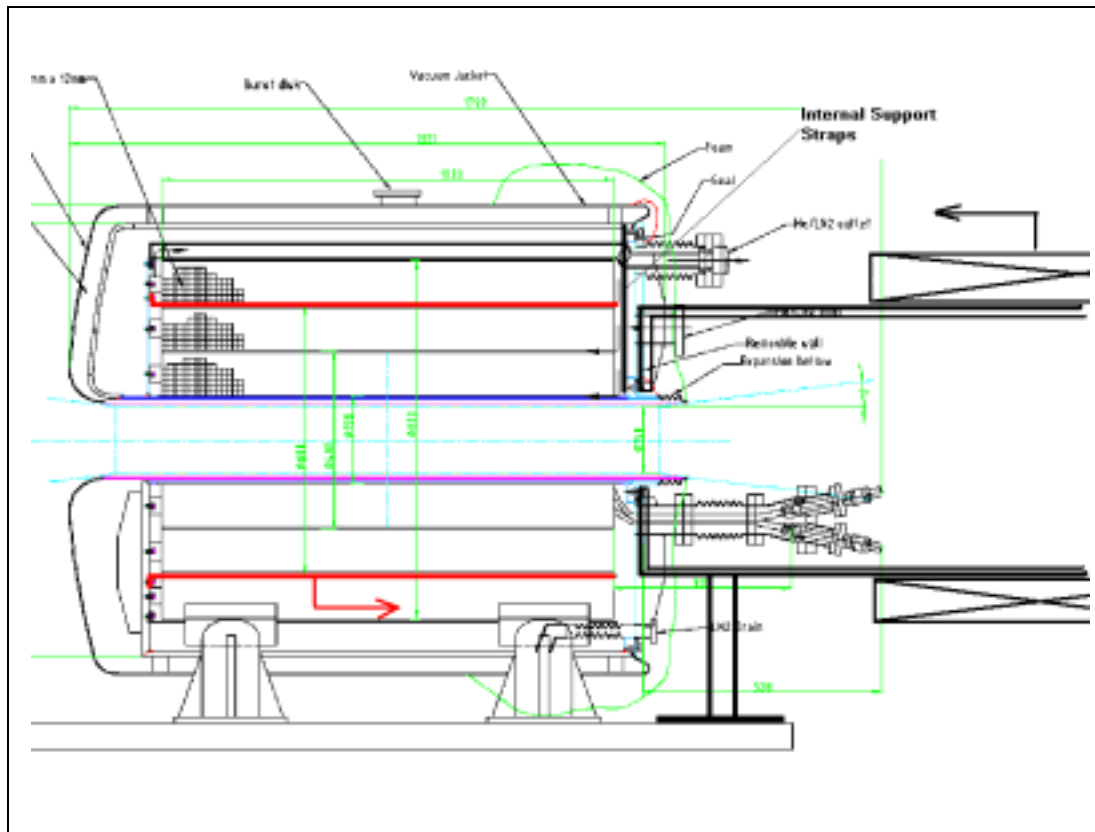
**Ribs are applied to outer surface of the wound and impregnated coil**

**Ribs are machined to match the ID of the next coil segment**

**Coils are slipped on to one another. – with a temperature difference if needed**



*Phased fabrication of the coil segments is the motivation for the mechanical head closure.*



The joint flanges are loosened, bellows compressed, and ceramaseal penetration set screws are loosened.

The ceramaseal connections are removed

Head lip seal welds (if used) are cut.

The closure head is removed. Internal support straps hold the coil weight.

The assembly shell is installed, bolted to the inner head bolt circle, Temporary supports/cribbing support the shell and coil weight. The internal support straps are removed.

The coolant shroud (red) is removed swapping inner and outer temporary supports.

The third coil segment is then slipped into place.

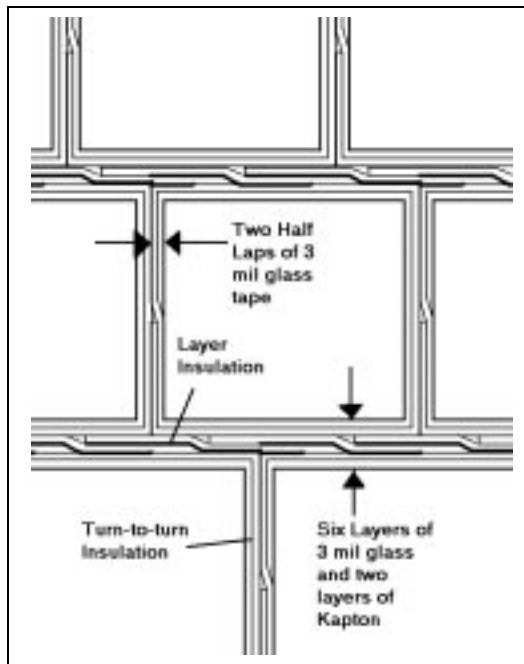
The internal support straps are replaced. The assembly shell is removed.

The head is replaced, and bolts torqued. The lip seal welds (if used) are made. The ceramaseal connections are re-made.



## Conductor Dimensions

with 2 millimeter channel tolerance  
 radial dim  $1.1669799 \times 10^{-2}$  m .45944 in  
 Axial dim  $1.3028533 \times 10^{-2}$  m .51293333 in  
 packing fraction= .95025227



## Layer Insulation

- Kapton is the limiting element in the thermal conduction through the coil.
- Kapton was expected to be wound around the conductor. This produced the equivalent of 5 mils of Kapton between layers.
- To improve conduction, Kapton is used only between the layers. Turn to turn voltage is lower than layer to layer. The turn to turn voltage is less than the rule of thumb for He breakdown voltage (1 volt/mil at 1 atmosphere) for the insulation thickness proposed.
- The layer to layer voltage exceeds this however, and would need the Kapton if there was an imperfection in the epoxy/glass insulation. Half lapps of kapton and fiberglass, similar to the CS model coil will retain some structural integrity.
- Once a layer of conductor is wound, a layer of Kapton/glass would be wound on the completed layer of conductor. This produces the thermal conduction equivalent of 3 mils of Kapton rather than 5 if the conductor is wrapped individually. Every 8th layer channel strips are layed on.

## Cryostat Bore Tube Geometry

Building from the Magnet ID and working towards the centerline:

Component	Thickness (m)	Radius (m)
The ID of the magnet winding		$.15-.98/2=.101$
Coolant Channel	.002	.099
Cold Cryostat Shell	.004762(3/16in.)	.094237
Vacuum Space	.008	.086237
Vacuum shell	.0005	.085737
Strip heater	.001	.084737

This leaves a clear bore diameter of .16947m

## **Help Needed:**

He Gas properties between 20K and 50K

Specification Boiler plate

Bore Heater Strip Vendor and Specifications (Willie Burke?)